HYDROGEOLOGY AND GROUND-WATER FLOW IN THE CARBONATE ROCKS OF THE LITTLE LEHIGH CREEK BASIN, LEHIGH COUNTY, PENNSYLVANIA

By Ronald A. Sloto, L. DeWayne Cecil, and Lisa A. Senior

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 90-4076

Prepared in cooperation with the

DELAWARE RIVER BASIN COMMISSION,
PENNSYLVANIA DEPARTMENT OF ENVIRONMENTAL RESOURCES,
LEHIGH COUNTY AUTHORITY,
CITY OF ALLENTOWN, and
SOUTH WHITEHALL TOWNSHIP

Lemoyne, Pennsylvania
1991

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
inches per year (in/yr)	25.4	millimeters per year (mm/yr)
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day (m/d)
square foot per day (ft^2/d)	0.09290	square meter per day (m^2/d)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
million gallons (Mgal)	3,785	cubic meter (m^3)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter [(L/s)/m]
gallon per day (gal/d)	0.00004381	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per square mile (ft^3/mi^2)	0.01093	cubic meter per square kilometer (m^3/km^2)
	Temperature	
degree Fahrenheit (°F)	°C=5/9 (°F-32)	degree Celsius (°C)

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level Datum of 1929."

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ABSTRACT

The Little Lehigh Creek basin is underlain mainly by a complex assemblage of highly-deformed Cambrian and Ordovician carbonate rocks. The Leithsville Formation, Allentown Dolomite, Beekmantown Group, and Jacksonburg Limestone act as a single hydrologic unit. Ground water moves through fractures and other secondary openings and generally is under water-table conditions. Median annual ground-water discharge (base flow) to Little Lehigh Creek near Allentown (station 01451500) during 1946-86 was 12.97 inches or 82 percent of streamflow. Average annual recharge for 1975-83 was 21.75 inches. Ground-water and surface-water divides do not coincide in the basin. Ground-water underflow from the Little Lehigh Creek basin to the Cedar Creek basin in 1987 was 4 inches per year. A double-mass curve analysis of the relation of cumulative precipitation at Allentown to the flow of Schantz Spring for 1956-84 showed that cessation of quarry pumping and development of ground water for public supply in the Schantz Spring basin did not affect the flow of Schantz Spring.

Ground-water flow in the Little Lehigh Creek basin was simulated using a finite-difference, two-dimensional computer model. The geologic units in the modeled area were simulated as a single water-table aquifer. The 134-square-mile area of carbonate rocks between the Lehigh River and Sacony Creek was modeled to include the natural hydrologic boundaries of the ground-water-flow system. The ground-water-flow model was calibrated under steady-state conditions using 1975-83 average recharge, evapotranspiration, and pumping rates. Each geologic unit was assigned a different hydraulic conductivity. Initial aquifer hydraulic conductivity was estimated from specific-capacity data. The average (1975-83) water budget for the Little Lehigh Creek basin was simulated. The simulated base flow from the carbonate rocks of the Little Lehigh Creek basin above gaging station 01451500 is 11.85 inches per year. The simulated ground-water underflow from the Little Lehigh Creek basin to the Cedar Creek basin is 4.04 inches per year. For steady-state calibration, the root-mean-squared difference between observed and simulated heads was 21.19 feet.

The effects of increased ground-water development on base flow and underflow out of the Little Lehigh Creek basin for average and drought conditions were simulated by locating a hypothetical well field in different parts of the basin. Steady-state simulations were used to represent equilibrium conditions, which would be the maximum expected long-term effect. Increased ground-water development was simulated as hypothetical well fields pumping at the rate of 15, 25, and 45 million gallons per day in addition to existing ground-water withdrawals. Four hypothetical well fields were located near and away from Little Lehigh Creek in upstream and downstream areas.

The effects of pumping a well field in different parts of the Little Lehigh Creek basin were compared. Pumping a well field located near the headwaters of Little Lehigh Creek and away from the stream would have greatest effect on inducing underflow from the Sacony Creek basin and the least effect on reducing base flow and underflow to the Cedar Creek basin. Pumping a well field located near the headwaters of Little Lehigh Creek near the stream would have less impact on inducing underflow from the Sacony Creek basin and a greater impact on reducing the base flow of Little Lehigh Creek because more of the pumpage would come from diverted base flow. Pumping a well field located in the downstream area of the Little Lehigh Creek basin away from the stream would have the greatest effect on the underflow to the Cedar Creek basin. Pumping a well field located in the downstream area of the Little Lehigh Creek basin near the stream would have the greatest effect on reducing the base flow of Little Lehigh Creek. Model simulations show that ground-water withdrawals do not cause a proportional reduction in base flow. Under average conditions, ground-water withdrawals are equal to 48 to 70 percent of simulated base-flow reductions; under drought conditions, ground-water withdrawals are equal to 35 to 73 percent of simulated base-flow reductions.

The hydraulic effects of pumping largely depend on well location. In the Little Lehigh basin, surface-water and ground-water divides do not coincide, and ground-water development, especially near surface-water divides, can cause ground-water divides to shift and induce ground-water underflow from adjacent basins. Large-scale ground-water pumping in a basin may not produce expected reductions of base flow in that basin because of shifts in the ground-water divide; however, such shifts can reduce base flow in adjacent surface-water basins.

INTRODUCTION

The carbonate rocks of the Little Lehigh Creek basin are an important source of water for residents of the Little Lehigh Creek basin and the nearby city of Allentown. Population in the Allentown area is rapidly growing and the demand for ground water is increasing. The hydrogeology of the carbonate rocks of the Little Lehigh Creek basin is complex because of the variable hydraulic characteristics of the various lithologies, complex structural relations, and karst terrane. This investigation by the U.S. Geological Survey (USGS) was made in cooperation with the Delaware River Basin Commission, the Pennsylvania Department of Environmental Resources, the Lehigh County Authority, the City of Allentown, and South Whitehall Township.

Purpose and Scope

This report describes the ground-water-flow system in the carbonate rocks and the hydrologic budget of the Little Lehigh Creek basin. The report also describes the development and use of a steady-state finite-difference model to: (1) simulate ground-water flow in the carbonate-rock aquifer system, (2) simulate the hydrologic budget for the 80.8 mi^2 (square mile) area of the Little Lehigh Creek basin above streamflow-gaging station 01451500, and (3) estimate the effect of increased ground-water pumping on the hydrologic budget.

The area of primary interest is underlain by the carbonate rocks in the Little Lehigh Creek basin. However, a larger area is modeled to include necessary hydrologic boundaries. The modeled area includes carbonate rocks in the Little Lehigh Creek basin and part of the Sacony Creek basin in Lehigh and Berks Counties. The study area is bordered on the east by the Lehigh River, on the west by Sacony Creek, on the north by the Martinsburg Formation, and on the south by Hardyston Quartzite.

Location and Physiography

The Little Lehigh Creek basin is located in central Lehigh County in eastern Pennsylvania (fig. 1). The drainage area of the Little Lehigh Creek basin is 190 mi^2, of which nearly 81 mi^2 is underlain by carbonate rocks. The main tributaries to Little Lehigh Creek are Jordan Creek (drainage area 82.3 mi^2) and Cedar Creek (drainage area 15.0 mi^2). The Little Lehigh Creek and its tributaries flow eastward, joining the Lehigh River near Allentown. On the western boundary, Sacony Creek drains to the Schuylkill River.

The Lehigh Valley is part of the Valley and Ridge physiographic province (fig. 2). The carbonate rocks that underlie the valley are the focus of this study. The Lehigh Valley is bordered on the north by ridge-forming noncarbonate rocks of the Martinsburg Formation. The Martinsburg Formation, together with carbonate-rock units, belong to the Lehigh Valley and Schuylkill Valley sequences. The Lehigh Valley is bordered to the south by the ridge-forming crystalline rocks of the Reading Prong section of the New England physiographic province.

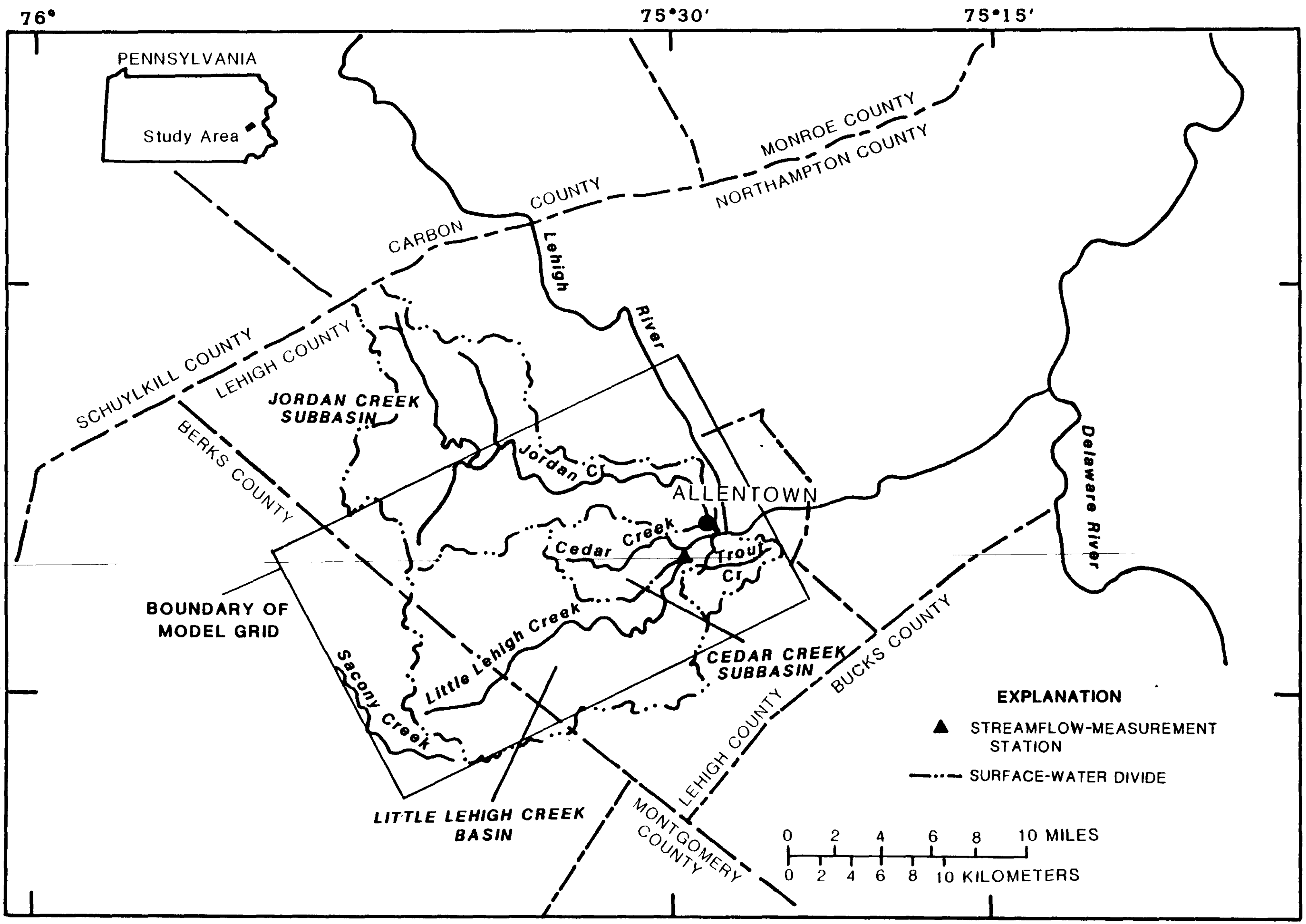


Figure 1.--Location of Little Lehigh Creek basin.

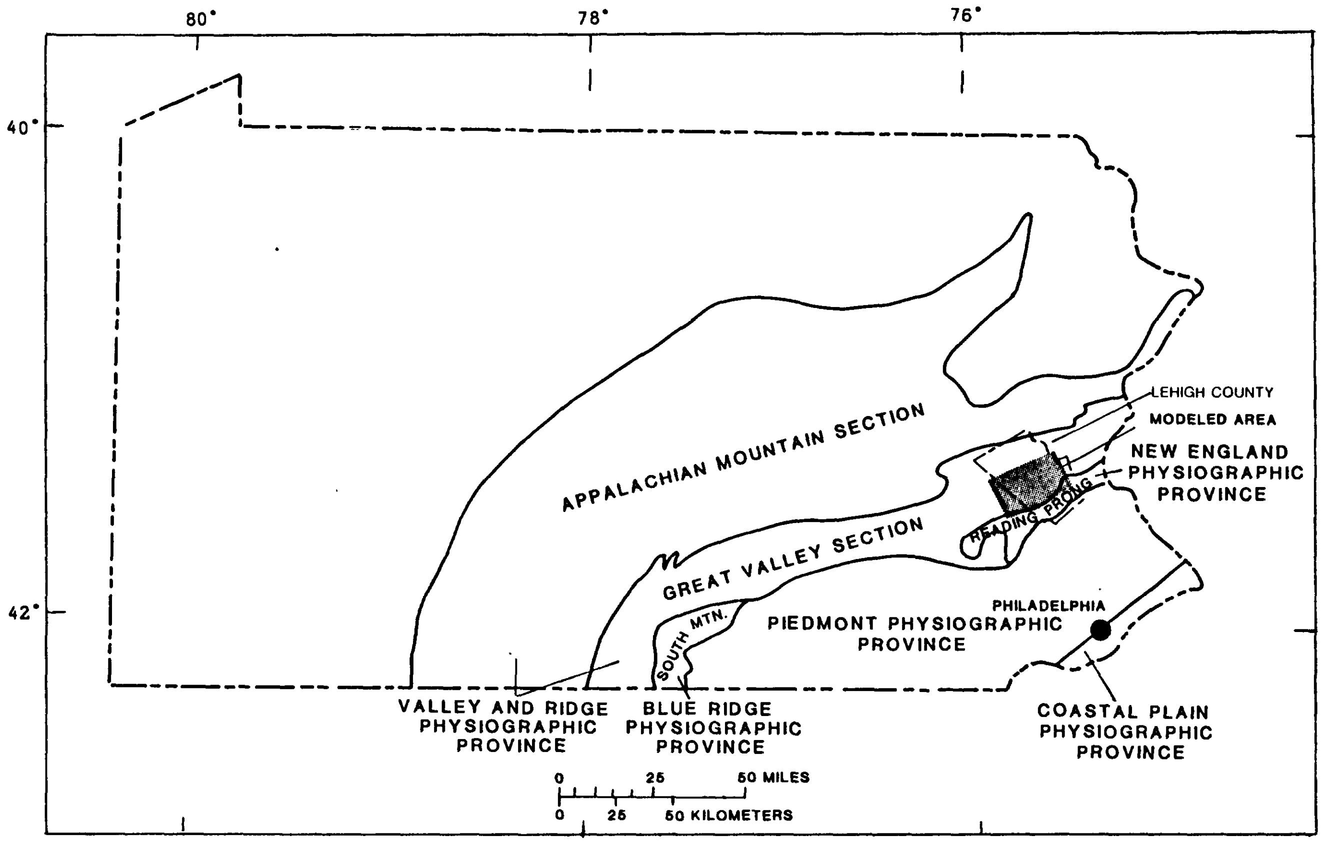


Figure 2.--Physiographic provinces.

Climate

The climate in the Lehigh Valley is temperate with relatively high humidity. Precipitation is nearly evenly distributed throughout the year, with slightly more in July and August than in other months. The 1951-80 normal precipitation at the Allentown-Bethlehem-Easton airport is 44.31 in/yr (inches per year) (National Oceanic and Atmospheric Administration, 1982). January is the coldest month; the 1951-80 average temperature for January is 27.3 °F (degrees Fahrenheit). July is the warmest month; the 1951-80 average temperature for July is 73.9 °F. The 1951-80 average annual temperature at the Allentown-Bethlehem-Easton airport is 51.1 °F.

Well-Numbering System

The well-numbering system used in this report consists of two parts: (1) a two-letter abbreviation that identifies the county in which the well is located, and (2) a sequentially-assigned number. All wells are in Berks or Lehigh counties and are identified by the prefixes BE and LE, respectively. Locations of selected wells, with the prefixes BE and LE omitted from the local well number, are shown on plate 1. The site-identification number given in table 18 has 15 digits. The first six digits denote the degrees, minutes, and seconds of latitude; the next seven digits denote the degrees, minutes, and seconds of longitude; and the last two digits denote a sequentially-assigned number to distinguish among sites located within a common 1-second grid block.

Previous Investigations

Miller (1941) described the geology of Lehigh County and included a discussion of ground-water resources. Wood and others (1972) described the water-resources of Lehigh County in detail. Drake (1960, 1965, 1978, and 1987) interpreted the structure and stratigraphy of the area. Kochanov (1987) mapped sink holes and other karst features.

Well data used for analysis in this study are given by Wood and others (1972, p. 228-263) for Lehigh County and Wood and MacLachlan (1978, p. 61-91) for Berks County. Additional data are given in table 18 in this report.

Acknowledgments

The cooperation of well owners and local, county, and state officials is gratefully acknowledged, especially the Lehigh County Authority (LCA) and the City of Allentown, for providing essential data. Additional data were provided by the Stroh Brewery Company, Gannett Fleming Geotechnical Engineers Inc., and the Lane Hydro Group, Inc.

HYDROGEOLOGY

The Little Lehigh Creek basin is underlain by highly-deformed Paleozoic carbonate rocks and is bordered by Paleozoic and older noncarbonate rocks that are more resistant to erosion. Both lithology and structure determine the geologic boundaries separating the carbonate and noncarbonate rocks. The Precambrian crystalline rocks of the Reading Prong and a Cambrian quartzite and other sediments are south of the northeast trending carbonate valley (fig. 2). Two series of deformed Paleozoic slates, shales, mudstones, and graywackes are north of the carbonate valley. The noncarbonate rocks to the north and south form geologic and hydrologic boundaries to the Lehigh Valley. Generally, ground-water and surface-water basin divides to the north and south of the Lehigh Valley coincide with ridge crests of the bordering noncarbonate rocks. Water enters the carbonate valley as precipitation and ground-water and surface-water flow from the flanking noncarbonate rocks.

Geology

The Little Lehigh Creek basin is underlain by a structurally-complex assemblage of Paleozoic carbonate and noncarbonate rocks (pl. 1). Several distinct sequences of rocks were emplaced as nappes, which are large overturned folds or major thrust slices. Due in part to the structural displacement of the rock sequences, stratigraphic relations change from east to west. The general stratigraphy is shown in figure 3. The oldest rocks are the Precambrian crystalline rocks of the Reading Prong that form the south flank of the valley. The youngest rocks are the shales, mudstones, and graywackes of the Middle Ordovician Martinsburg Formation that form the north flank of the valley. Other younger, unconsolidated material, such as till and drift deposited during Illinoian glaciation, partly covers the carbonate rocks of Lehigh Valley and the bordering northern noncarbonate rocks. General geology, mapping, and description of geologic units and structure has been compiled for this report from many sources (Drake, 1960, 1965, 1978, and 1987; Lash, 1985; Miller, 1941; Poth, 1972; Wood and others, 1972; MacLachlan, 1979 and 1983; MacLachlan and others, 1975; Berg and Dodge, 1981; Berg and others, 1986; Lyttle and Epstein, 1987; Hobson, 1963; Kochanov, 1987).

Stratigraphy of the Carbonate Rocks

The carbonate rocks of the Little Lehigh Creek basin lie within the eastern end of the Great Valley section of the Valley and Ridge physiographic province (fig. 2) and have been divided into two related stratigraphic sequences by MacLachlan (1967, 1983). The Schuylkill Valley sequence crops out in the southwestern part of the Little Lehigh Creek basin and is separated from the Lehigh Valley sequence by the Black River thrust fault. The Schuylkill Valley sequence is similar to the Lehigh Valley sequence, but differs from it by the presence of the Stonehenge Limestone and the Ontelaunee Formation, the absence of the Jacksonburg cement rock facies of the Jacksonburg Limestone, and the occurrence of limestone and magnesium limestone in the Tuckerton Member of the Allentown Dolomite. Generally, the ages of the carbonate rocks exposed in the Lehigh Valley are progressively younger from south to north, and where not structurally dislocated, represent a continuous stratigraphic sequence from Lower Cambrian to Middle Ordovician.

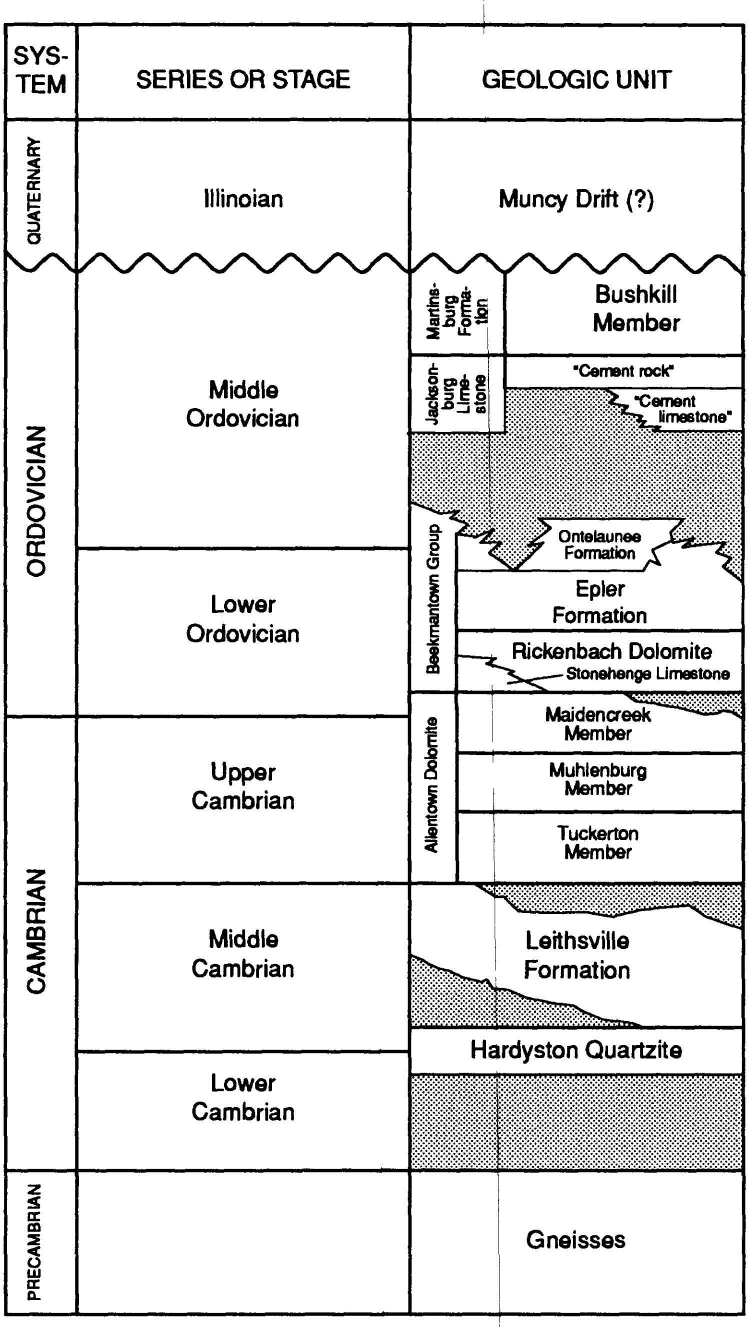


Figure 3.--Generalized stratigraphic column for Schuylkill and Lehigh Valley sequences. (Modified from Lash and Drake 1985, and Lyttle and Epstien 1987).

Leithsville Formation

The Lower to Middle Cambrian Leithsville Formation is the oldest carbonate unit exposed in the study area and is conformable or in fault contact with the underlying Lower Cambrian Hardyston Quartzite. The Leithsville Formation is a medium to dark-medium gray, thick-bedded, finely-crystalline dolomite with shaly beds in the upper part. The formation is about 400 ft (feet) thick.

Allentown Dolomite

The Upper Cambrian and Lower Ordovician Allentown Dolomite has three members: the Tuckerton (lower), Muhlenberg (middle), and Maidencreek (upper). Total thickness of the Allentown Dolomite is about 2,500 ft. The Tuckerton Member is a light to dark-medium gray, medium- to thick-bedded dolomite. In the Schuylkill Valley sequence, it contains magnesium limestone and limestone with limey beds having silty or shaly partings. The Tuckerton Member is 500 to 650 ft thick. The Muhlenberg Member is a medium gray, thick-bedded dolomite and magnesium limestone containing interbedded calcareous and limonitic sandstone. The Muhlenberg Member is about 800 ft thick. The Maidencreek Member is a medium to dark-medium gray, thick-bedded dolomite and magnesium limestone containing chert stringers and nodules. The Maidencreek Member is about 1,200 ft thick.

Beekmantown Group

The Beekmantown Group includes four units in ascending order: the Stonehenge Limestone, the Rickenbach Dolomite, the Epler Formation, and the Ontelaunee Formation. Total thickness of the Beekmantown Group is about 2,100 ft. The Lower Ordovician Stonehenge Limestone is a medium gray, medium- to thick-bedded, finely-crystalline limestone with silty or sandy laminae, sporadic beds, lenses of fossil hash, and intraformational conglomerate. It has dolomite beds near the base. The Stonehenge Limestone is about 400 ft thick. The Lower Ordovician Rickenbach Dolomite is a medium to dark-medium gray, medium- to coarsely-crystalline dolomite containing chert rosettes and gray, finely-crystalline dolomite with chert nodules, lenses, and beds. The Rickenbach Dolomite is about 500 ft thick. The Lower Ordovician Epler Formation is a medium to dark-medium gray, finely-crystalline, silty limestone interbedded with some thin- to thick-bedded cryptocrystalline dolomite. The Epler Formation is about 650 ft thick. The Lower to Middle Ordovician Ontelaunee Formation is a medium to dark gray, medium- to thick-bedded, very-finely- to finely-crystalline limestone with some medium-bedded, medium-crystalline dolomite. It has dark gray chert beds and nodules near the base. Thickness of the Ontelaunee Formation is about 500 ft. Its upper contact is a fault.

Jacksonburg Limestone

The Middle Ordovician Jacksonburg Limestone of the Lehigh Valley sequence differs from the Jacksonburg Limestone of the Schuylkill Valley sequence by the presence of cement limestone. The Jacksonburg Limestone of the Lehigh Valley sequence is divided into a cement limestone and cement rock facies. The cement limestone facies is a light to medium gray, medium- to coarse-grained calcarenite and fine- to medium-crystalline high-calcium limestone. The lower contact with the Beekmantown Group is a fault in most places. The cement limestone facies is about 350 ft thick. The cement-rock facies is dark gray to black, fine- to medium-grained limestone with scattered, thin beds of crystalline limestone; bedding commonly is obliterated by slaty cleavage. The cement rock facies is about 400 ft thick. The upper contact of the unit is a fault in places.

The Jacksonburg Limestone, undivided, of the Schuylkill Valley sequence is a dark gray to black, laminated to medium-bedded, fine-grained argillaceous limestone with some crystalline limestone and calcareous limestone beds. Lower and upper contacts are mostly faults, but, in places, the Jacksonburg Limestone disconformably overlies the Ontelaunee Formation.

Stratigraphy of the Noncarbonate Rocks

The oldest noncarbonate rocks, the Precambrian crystalline rocks of the Reading Prong and the Lower Cambrian Hardyston Quartzite, form the southern boundary of the Lehigh Valley. The Reading Prong is comprised of a structurally-complex series of metamorphosed gneisses of different compositions and is the detached core of a recumbent nappe. Hardyston Quartzite unconformably overlies the gneiss. It is light gray, medium- to thick-bedded quartzite and feldspathic sandstone with a basal quartz-pebble conglomerate. The Hardyston Quartzite ranges from 100 to more than 800 ft thick.

The noncarbonate rocks forming the northern border of the Lehigh Valley belong to several different stratigraphic sequences--the related Lehigh Valley and Schuylkill Valley sequences in the eastern and central section of the study area and the Hamburg klippe in the western section of the study area.

The Middle Ordovician Bushkill Member of the Martinsburg Formation is stratigraphically above the Middle Ordovician Jacksonburg Limestone of the Schuylkill and Lehigh Valley sequences. The Bushkill Member is lithologically similar in both sequences and is a medium to dark gray slate containing some thin beds of quartzose slate, graywacke, siltstone, and carbonaceous slate. The Bushkill Member thickens westward from 2,800 to 4,000 ft.

To the west and south of the Martinsburg Formation, the noncarbonate rocks bordering the Lehigh Valley belong to the Lower and Middle Ordovician Windsor Township Formation of the Hamburg klippe, an allochthonous stratigraphic sequence. The Windsor Township Formation has several mapped members and consists of shales, mudstones, siltstones, and graywackes. The Windsor Township Formation is more than 990 ft thick.

Structure and Regional Setting

Regional structure of the area is explained as a series of large overturned folds and major thrust slices (Drake, 1978 and 1987). The observed complex structures are a result of repeated deformation of the rock units. More than four episodes of folding and more than two episodes of faulting are recognized (Drake, 1987). Major deformation occurred during the Taconic Orogeny in the Late Ordovician, and further deformation occurred in the Allegheny Orogeny in the Late Permian. Regionally, the strike of structures and geologic units is northeast, with folded beds, thrust faults, and thrust slices dipping to the south or southeast. Locally, structures may not follow this pattern because of multiple deformations, high-angle offset faults, and antiformal or synformal attitudes.

Faults commonly separate geologic units in the Lehigh Valley. The Reading Prong units and overlying Hardyston Quartzite most commonly are in thrust fault contact with the Leithsville Formation, which is lowest in the carbonate sequence. North of this contact is the Black River thrust fault that brings the Schuylkill Valley sedimentary sequence over the Lehigh Valley sequence. Within each of these sequences, the Beekmantown Group is thrust north over the Jacksonburg Limestone, and both of the carbonate sequences are thrust north over the Bushkill Member of the Martinsburg Formation and the allochthonous Hamburg klippe. Cross-sections (fig. 4) of the structure in the western section of the modeled area show the Black River thrust fault and fault contacts between carbonate units and shales of the Martinsburg Formation. Complex structures include windows or fault-bound slices of formations belonging to a different stratigraphic sequence such as the Cherry Hill window (fig. 4), overturned folds and faults, and refolded folds and faults.

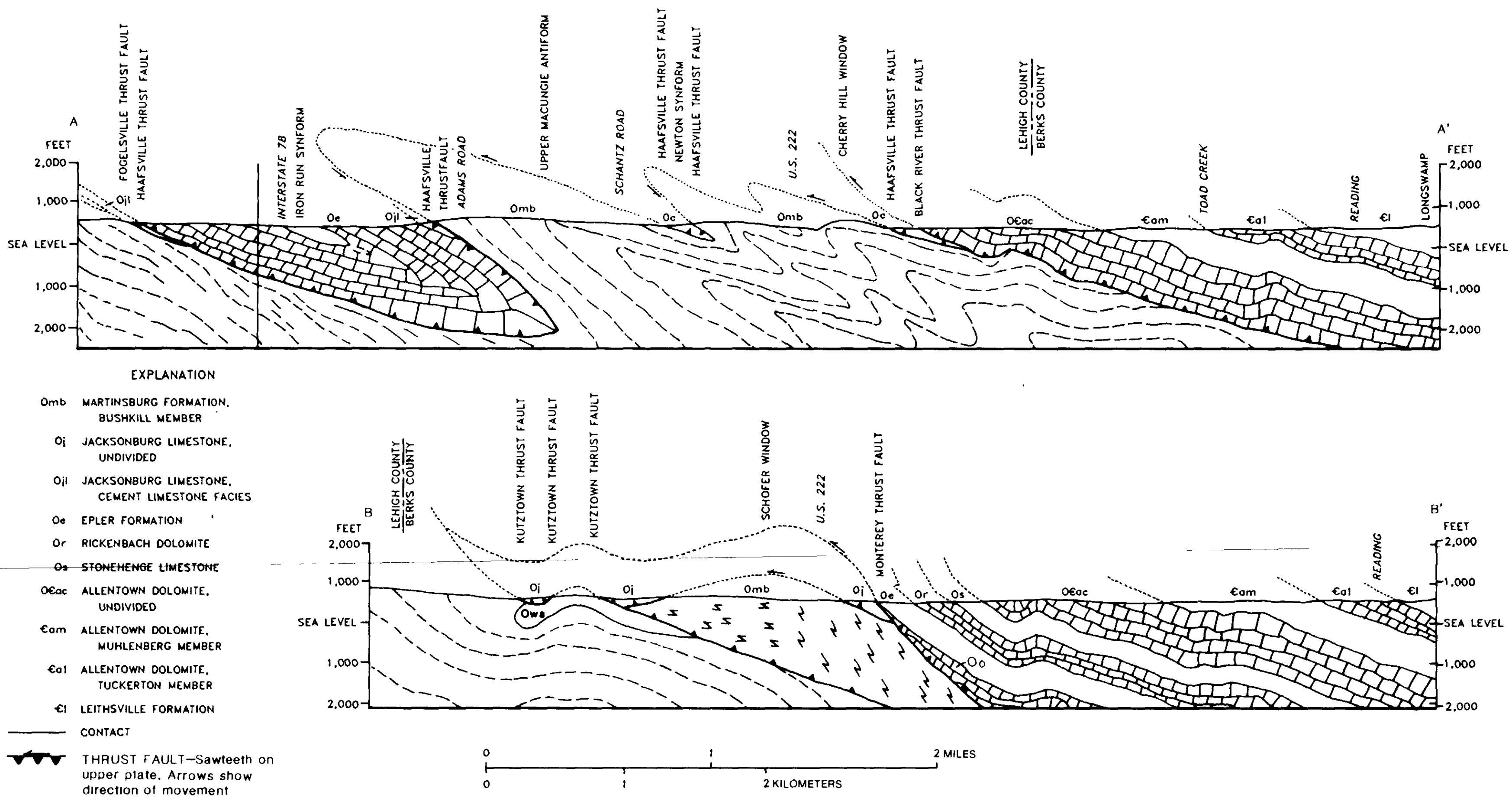


Figure 4.--Geologic sections showing carbonate and noncarbonate rocks near the Lehigh-Berks County order.

Geomorphology

Ongoing processes of physical and chemical weathering and past glacial processes are responsible for the reshaping of landforms following the major mountain-building events that occurred during the Paleozoic. Bordering the Lehigh Valley to the north, the shales, mudstones, and graywackes of the Martinsburg Formation and Hamburg klippe form ridges and steep-sided, hilly terrain. To the south of the Lehigh Valley, the Reading Prong complex forms rolling highlands. The carbonate rocks of the Lehigh Valley are more susceptible to erosion and form the gently rolling to nearly flat lowlands of the valley. The Jacksonburg Limestone cement rock is the most resistant to erosion of the carbonate rocks. Windows of rock units, such as the Cherry Hill window (fig. 4), often expose rocks more or less resistant to erosion and create knobs or depressions in the valley terrain.

Karst features

Karst features, such as the numerous sinkholes in the Lehigh Valley, are caused by dissolution of the carbonate rocks (fig. 5). Closed depressions where surface water may accumulate are common. Dissolution enlarges fracture and fault openings that, in part, control some stream paths. These fractures and faults may be expressed at the surface as fracture traces. Sinkholes are fairly evenly distributed in the rocks of the Beekmantown Group and Allentown Dolomite, with about 40 percent of the total in each lithology. The Jacksonburg Limestone is the most resistant unit to sinkhole development. Sinkhole distribution was mapped by Kochanov (1987). Karst features can act as conduits for ground-water recharge and generally increase the permeability of bedrock aquifers.

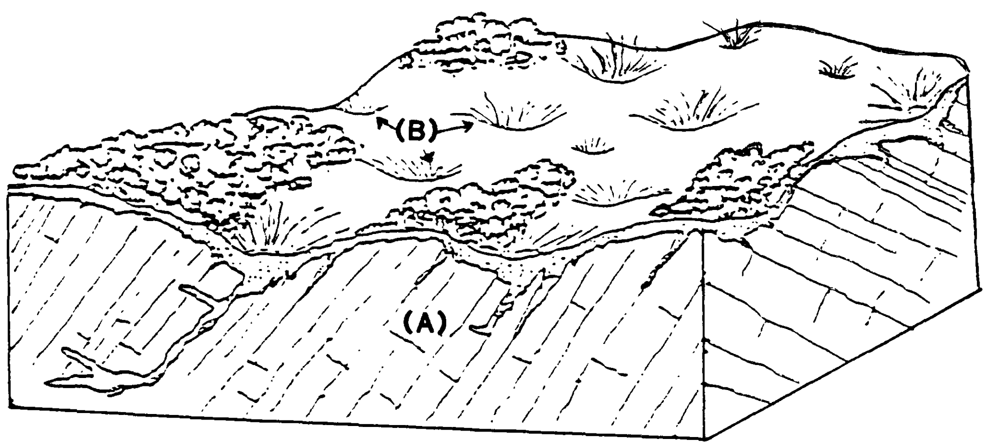


Figure 5.--Block diagram showing the relation between carbonate bedrock (A) and surface topography in karst areas. Note closed basins (B). (From Kochanov, 1987.)

Glacial features

Only deposits from the Illinoian glaciation extend as far south as the Lehigh Valley. The exact extent of Illinoian and possible pre-Illinoian ice is not known and has been delineated differently by various workers (Leverett, 1934; Poth, 1972; Epstein and others, 1974; Sevon and others, 1975; Braun, 1988). The extent of Illinoian glaciation described by Poth (1972) is shown in figure 6. From the Delaware River and the Blue Mountain Ridge, glacial deposits thin to the south and west toward the Lehigh Valley. Thickness of glacial deposits on the carbonate rocks in the eastern part of the study area range from a thin veneer to 120 ft (Miller, 1941); the thickest accumulation is in stream valleys. Deposits tentatively are identified as Muncy drift. Glacial erratics and stratified clays have been observed in the study area (Miller, 1941; Myers and Perlow, 1984).

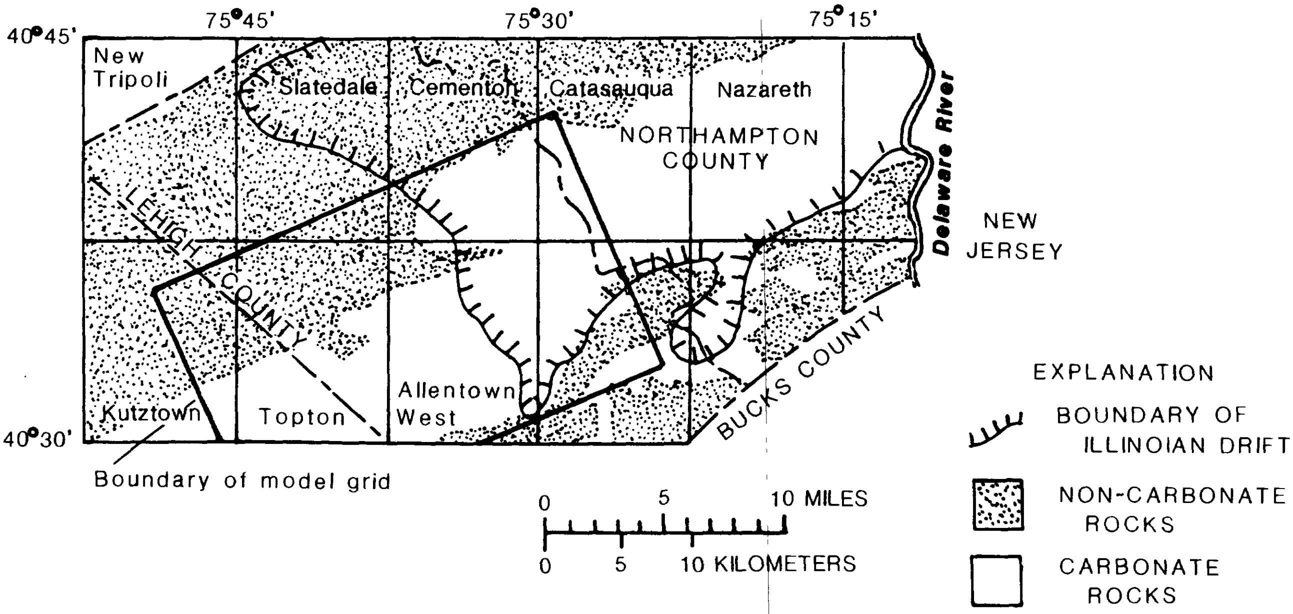


Figure 6.--Extent of Illinoian drift in Lehigh County. (From Poth 1972.)

Hydrology

In the Little Lehigh Creek basin, the Leithsville Formation, Allentown Dolomite, Beekmantown Group, and Jacksonburg Limestone act as a single hydrologic unit. Ground water moves through fractures and other secondary openings in these carbonate rocks. The carbonate aquifer system is generally under water-table conditions, but confined conditions exist locally.

A minor perched water-table aquifer in the glacial deposits exists locally in the central part of the study area. This aquifer is of limited areal extent; its presence is indicated by marshy and wet areas. The average saturated thickness of this system is about 30 ft. It is separated from the bedrock system by a low-permeability clay. In some places, stratified clay deposits are up to 10 ft thick.

Hydraulic Characteristics of Carbonate Rocks

Secondary porosity and permeability exhibit great spatial variation in carbonate rocks; therefore, the yield and specific capacity of wells are highly variable. Well yield depends on the number and size of openings penetrated below the water table--the more water-bearing openings intersected and the larger their size, the greater the well yield. The reported yield and specific capacity of wells in the modeled area are summarized in tables 1 and 2, respectively.

The reported yield and specific capacity of nondomestic wells generally is an order of magnitude greater than the yield and specific capacity of domestic wells (tables 1 and 2). Nondomestic wells generally are drilled deeper, penetrate more water-bearing zones, and have larger diameters than domestic wells. Data from nondomestic wells give a better estimate of aquifer hydraulic characteristics than data from domestic wells.

Table 1.--Reported yields of wells
[Yields are in gallons per minute; <, less than]

Geologic unit	All wells			Nondomestic wells			Domestic wells		
	Number of wells	Range	Median	Number of wells	Range	Median	Number of wells	Range	Median
Martinsburg Formation	42	1- 100	13	5	25- 100	25	37	1- 50	10
Jacksonburg Limestone	41	1-1,200	20	9	8-1,200	75	32	1- 200	17
Beekmantown Group	79	<1-2,000	35	27	10-2,000	150	52	<1- 500	17
Allentown Dolomite	122	5-1,500	55	36	17-1,460	150	86	5-1,500	30
Leithsville Formation	56	2-1,000	53	18	19- 850	250	38	2-1,000	25
Hardyston Quartzite	23	1- 530	35	10	14- 530	88	13	1- 150	15

Table 2.--Reported specific capacity of wells
[Specific capacity is in gallons per minute per foot of drawdown; <, less than; --, no data]

Geologic unit	All wells			Nondomestic wells			Domestic wells		
	Number of wells	Range	Median	Number of wells	Range	Median	Number of wells	Range	Median
Martinsburg Formation	14	0.04- 13	0.69	0	--	--	14	0.04- 13	0.69
Jacksonburg Limestone	16	<.01- 34	1.2	5	0.27- 34	1.3	11	<.01- 12	.29
Beekmantown Group	30	<.01-330	9.8	18	.02-330	25	12	<.01-125	2.0
Allentown Dolomite	48	.03-125	4.3	23	.14-125	8.3	25	.03-115	2.1
Leithsville Formation	28	.18-375	2.4	10	2.2 -175	5.3	18	.18-375	1.3
Hardyston Quartzite	15	<.01- 18	.60	8	.39- 18	1.5	7	<.01-.77	.37

Yields of 79 wells in the Beekmantown Group in the modeled area range from 0.5 to 2,000 gal/min (gallons per minute). Only one yield exceeds 1,000 gal/min. The median yield of 27 nondomestic wells is 150 gal/min. Wells in the Beekmantown Group have a higher median specific capacity than wells in other carbonate units. The specific capacities of 30 wells range from less than 0.01 to 330 (gal/min)/ft (gallons per minute per foot) of drawdown; the median specific capacity of 18 nondomestic wells is 25 (gal/min)/ft.

Aquifer tests were conducted on two wells in the Epler Formation of the Beekmantown Group. A 70-hour aquifer test of well LE-1319 was conducted September 9-12, 1985, by a private contractor. The pumping rate ranged from 1,000 to 2,000 gal/min and averaged 1,900 gal/min. Drawdown in LE-1319 was 6 ft after 70 hours. Drawdowns were measured in five observation wells. The transmissivity, based on analysis of the aquifer-test data by the Cooper-Jacob method (Lohman, 1979, p. 19-23), was 33,000 ft^2/d (square feet per day).

A 74-hour aquifer test of well LE-1355 was conducted February 11-14, 1986, by a private contractor. The pumping rate was 1,400 gal/min. Drawdown in LE-1355 was 24 ft after 73 hours. Drawdowns were measured in eight observation wells. Transmissivity, based on analysis of the aquifer-test data by the Cooper-Jacob method, was 44,400 ft^2/d.

Yields of 122 wells in the Allentown Dolomite in the modeled area range from 5 to 1,500 gal/min. Only four yields exceed 600 gal/min. The median yield of 36 nondomestic wells is 150 gal/min. Specific capacities of 48 wells range from 0.03 to 125 (gal/min)/ft; the median specific capacity of 23 nondomestic wells is 8.3 (gal/min)/ft.

Specific capacities of wells on hilltops in the Allentown Dolomite are much lower than specific capacities of wells in valleys. Specific-capacity data for wells in Lehigh County analyzed by topographic position by Wood and others (1972, p. 117) showed that wells in valleys had a median specific capacity of 33 (gal/min)/ft, whereas wells on hilltops had a median specific capacity of 1.2 (gal/min)/ft. The rock underlying valleys tends to be more fractured and more transmissive than rock underlying hilltops.

Nondomestic wells in the Leithsville Formation have a greater median yield than nondomestic wells in the other carbonate-rock units. Yields of 56 wells in the Leithsville Formation in the modeled area range from 2 to 1,000 gal/min; the median yield of 18 nondomestic wells is 250 gal/min. Specific capacities of 28 wells range from 0.18 to 375 (gal/min)/ft; the median specific capacity of 10 nondomestic wells is 5.3 (gal/min)/ft.

The Jacksonburg Limestone is the lowest-yielding carbonate-rock unit in the modeled area. Yields of 41 wells in the Jacksonburg Limestone in the modeled area range from 1 to 1,200 gal/min; however, only three yields exceed 200 gal/min. The median yield of nine nondomestic wells is 75 gal/min. Wells in the Jacksonburg Limestone have a lower median specific capacity than wells in the other carbonate units. Specific capacities of 16 wells range from less than 0.01 to 34 (gal/min)/ft; the median specific capacity of five nondomestic wells is 1.3 (gal/min)/ft.

Hydraulic Characteristics of Noncarbonate Rocks

Noncarbonate rocks underlie ridges north and south of the carbonate rocks. The Bushkill Member of the Martinsburg Formation is north of the carbonate valley, and the Hardyston Quartzite is south of the carbonate valley.

Water in the noncarbonate rocks moves through relatively narrow fractures, such as joints, bedding partings, and faults. Unlike those in the carbonate rocks, these fractures are not enlarged by solution, and the noncarbonate rocks have a much lower hydraulic conductivity than carbonate rocks. Generally, yields (table 1) and specific capacities (table 2) of wells in the noncarbonate rocks are much lower than the yields and specific capacities of wells in the carbonate rocks. Some wells drilled into the noncarbonate rocks, especially those near the contact with carbonate rocks, are drilled through the noncarbonate rocks and derive water from the more permeable underlying carbonate rocks.

In the noncarbonate rocks, local streams act as drains for the ground-water system. Ground-water flow is local, flow paths are short, and ground water discharges to nearby streams draining the noncarbonate rock. Some ground water flows from the noncarbonate rocks to adjacent carbonate rocks.

The noncarbonate rocks are not as permeable as the carbonate rocks. Wood and others (1972, p. 103-104) estimated that overland runoff to streams underlying only noncarbonate rock was about 35 percent, whereas overland runoff to streams underlying only carbonate rock was 10 percent.

The Bushkill Member of the Martinsburg Formation is an aquifer with very low yield. The median specific capacity of 14 domestic wells drilled into the Bushkill Member is 0.69 (gal/min)/ft (table 2), which is the lowest median specific capacity of any geologic unit in the Little Lehigh Creek basin. Specific-capacity data are not available for nondomestic wells. The median yield of five nondomestic wells drilled into the Bushkill Member is 25 gal/min (table 1), which is the lowest median yield of any geologic unit in the Little Lehigh Creek basin.

The median specific capacity of nondomestic wells drilled into the Hardyston Quartzite is higher than the median specific capacity of nondomestic wells drilled into the Jacksonburg Limestone, but lower than the median specific capacity of nondomestic wells drilled into the other carbonate units. The median specific capacity of nondomestic wells drilled into the Hardyston Quartzite is 1.5 (gal/min)/ft (table 2). The median yield of 10 nondomestic wells drilled into the Hardyston is 88 gal/min (table 1).

Water-Bearing Zones

Primary porosity in the carbonate rocks of the Lehigh Valley is virtually nonexistent. Occasional lenses of sand and gravel in the Leithsville Formation or Allentown Dolomite contain primary openings that yield a small quantity of water to wells (Wood and others, 1972, p. 105). However, most ground water flows through a network of interconnected secondary openings--fractures, joints, faults, parting planes, and bedding planes. Some of these openings have been enlarged by solution. The number and size of the openings determines the secondary porosity of the rock; the degree of interconnection of the openings determines the secondary permeability. The high permeability of carbonate rock is predominantly the result of enlargement of secondary openings by solution. Where solution has been active, permeability can be high; elsewhere, the same unit can be nearly impermeable.

Most openings enlarged by solution are only a fraction of an inch wide, but they are capable of high yields. Driller's records indicate that no more than 5 percent of all wells drilled into carbonate rock in Lehigh County penetrate water-bearing openings larger than 1 ft, although water-bearing zones as wide as 15 ft have been reported (Wood and others, 1972, p. 107).

Geophysical logs are used to identify fractures and water-bearing zones in fractured rock, in addition to providing other information. The caliper log of well LE-1319 (fig. 7) shows a 4-ft-wide fracture between 167 and 171 ft below land surface. This water-bearing zone produces 2,000 gal/min. The temperature, short normal resistivity, and spontaneous potential logs also show this major water-bearing zone. The caliper log shows minor fractures at 143, 162, and 185 ft below land surface.

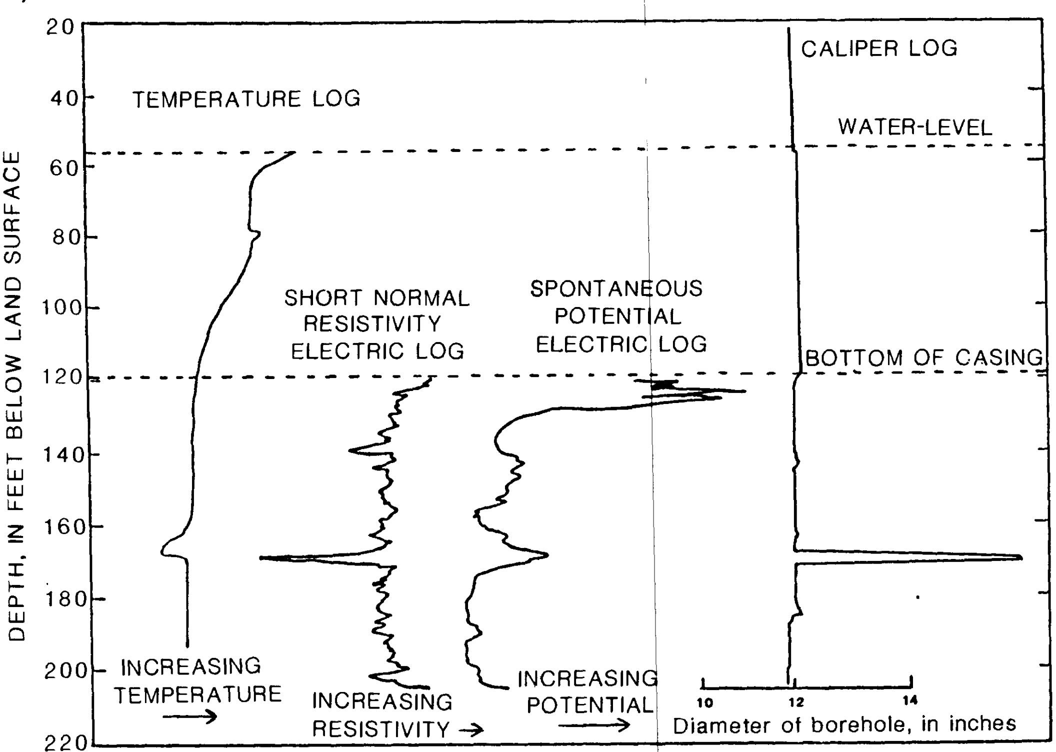


Figure 7.--Geophysical logs of well LE-1319.

The frequency of occurrence of water-bearing zones decreases with depth. The distribution of 425 water-bearing zones in 191 wells in the Jacksonburg Limestone, Beekmantown Group, Allentown Dolomite, and Leithsville Formation in the modeled area was analyzed (table 3). These wells represent 27,228 ft of uncased borehole, with well depths up to 907 ft. Fifty-one percent of the water-bearing zones are within 150 ft of land surface, and 82 percent are within 250 ft of land surface. Only 4 percent of the water-bearing zones are below a depth of 350 ft. Table 3 shows that more than two water-bearing zones per 100 ft of uncased borehole were encountered in the upper 100 ft, more than one water-bearing zone per 100 ft in the upper 350 ft, and less than one water-bearing zone per 100 ft below 350 ft. The large number of water-bearing zones per 100 ft below a depth of 650 ft is because of small sample size.

Table 3.--Number of water-bearing zones per 100 feet of uncased borehole drilled in carbonate rock

Depth interval (feet)	Number of water-bearing zones penetrated	Uncased footage drilled (feet)	Number of water-bearing zones per 100 feet of uncased borehole
0- 50	44	1,177	3.74
51-100	98	4,024	2.44
101-150	75	5,349	1.40
151-200	79	4,959	1.59
201-250	51	3,542	1.44
251-300	36	2,844	1.27
301-350	23	1,743	1.32
351-400	7	1,040	.67
401-450	2	675	.30
451-500	3	503	.60
501-550	2	382	.52
551-600	1	350	.29
601-650	1	300	.33
651-700	2	133	1.50
Below 700	1	207	[a].48

[a] Only one water-bearing zone was encountered in the interval 701-907 feet below land surface at 904 feet.

Ground-Water/Surface-Water Relations

The ground-water and surface-water systems are well connected in the Little Lehigh Creek basin. In the eastern part of the basin, ground water discharges to streams and comprises the base-flow component of streamflow. Ground-water discharge (base flow) made up 69 (in 1979) to 92 (in 1966) percent of the annual flow of Little Lehigh Creek at the streamflow-gaging station near Allentown (station 01451500) during 1946-86 (table 4). The median ground-water discharge was 82 percent of streamflow. Base-flow separations were made on hydrographs of Little Lehigh Creek using the computer program of Sloto (1991). The local minimum hydrograph-separation technique was used. The average annual base flow of Little Lehigh Creek ranged from 5.24 in. (inches) or 31.2 ft^3/s (cubic feet per second) in 1965 to 21.74 in. or 129 ft^3/s in 1984; the median base flow for 1946-86 was 12.97 in. or 77.2 ft^3/s. Figure 8 shows streamflow and base-flow hydrographs of Little Lehigh Creek for 1965, the year of lowest base flow, and 1984, the year of greatest base flow.

Table 4.--Base flow of Little Lehigh Creek near Allentown, 1946-86

Year	Base flow (inches)	Percentage of streamflow as base flow
1946	15.27	87.4
1947	13.01	87.6
1948	16.10	83.9
1949	14.36	88.9
1950	11.75	88.0
1951	17.19	85.3
1952	21.39	79.9
1953	21.15	83.5
1954	10.16	83.7
1955	12.68	80.2
1956	12.97	83.9
1957	10.00	81.2
1958	13.10	75.7
1959	8.93	80.4
1960	11.95	84.5
1961	11.02	86.8
1962	9.50	77.3
1963	8.26	80.6
1964	7.87	84.2
1965	5.24	87.5
1966	5.42	91.9
1967	8.30	84.5
1968	9.74	84.4
1969	7.64	79.8
1970	10.71	82.4
1971	17.99	77.2
1972	21.07	76.8
1973	21.63	81.8
1974	17.89	85.4
1975	21.50	80.7
1976	15.05	79.8
1977	15.08	78.6
1978	17.81	76.9
1979	18.15	68.6
1980	12.21	88.4
1981	6.76	87.2
1982	10.78	78.6
1983	15.71	71.2
1984	21.74	71.4
1985	9.66	77.0
1986	14.61	77.2
Median	12.97	81.8

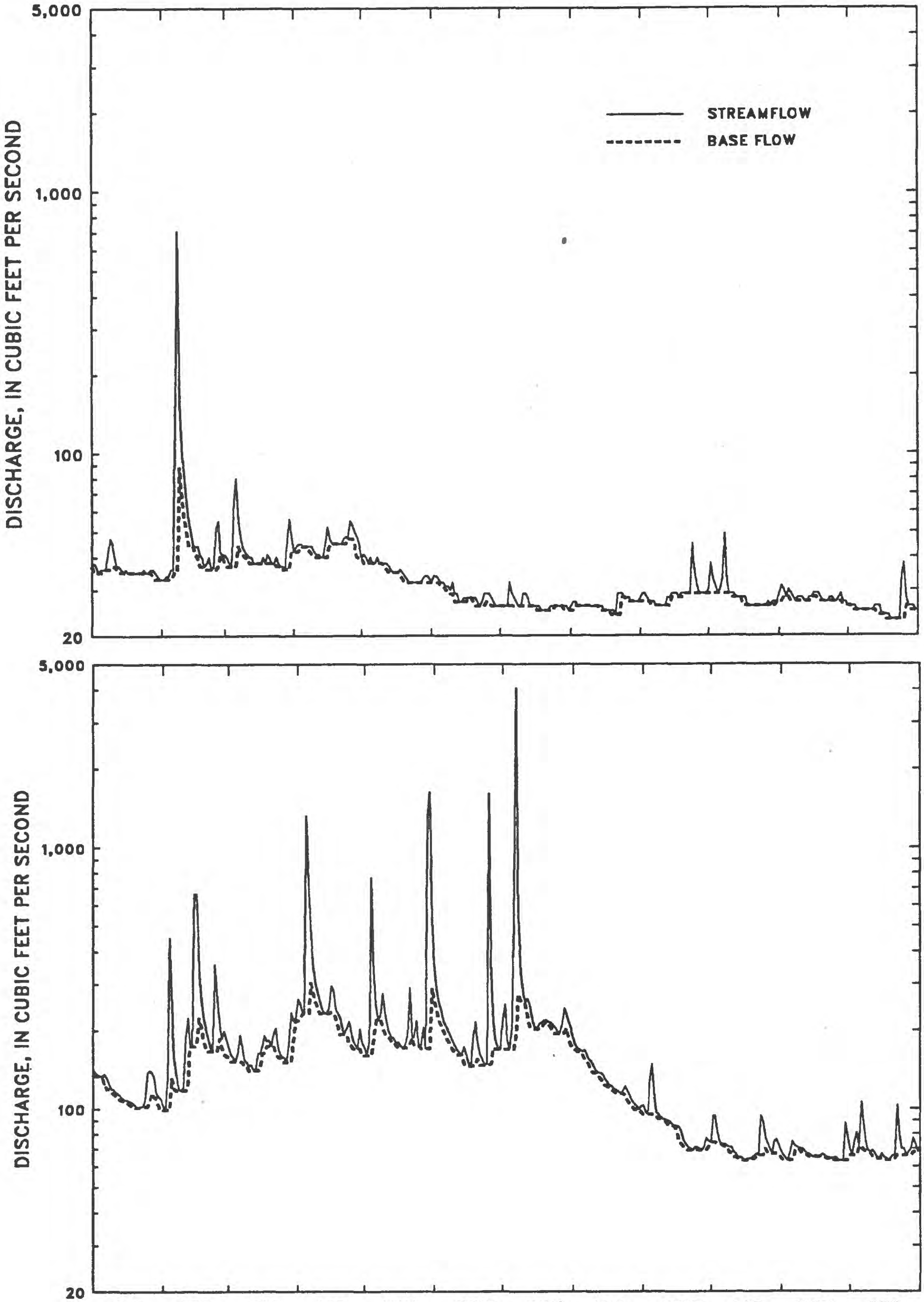
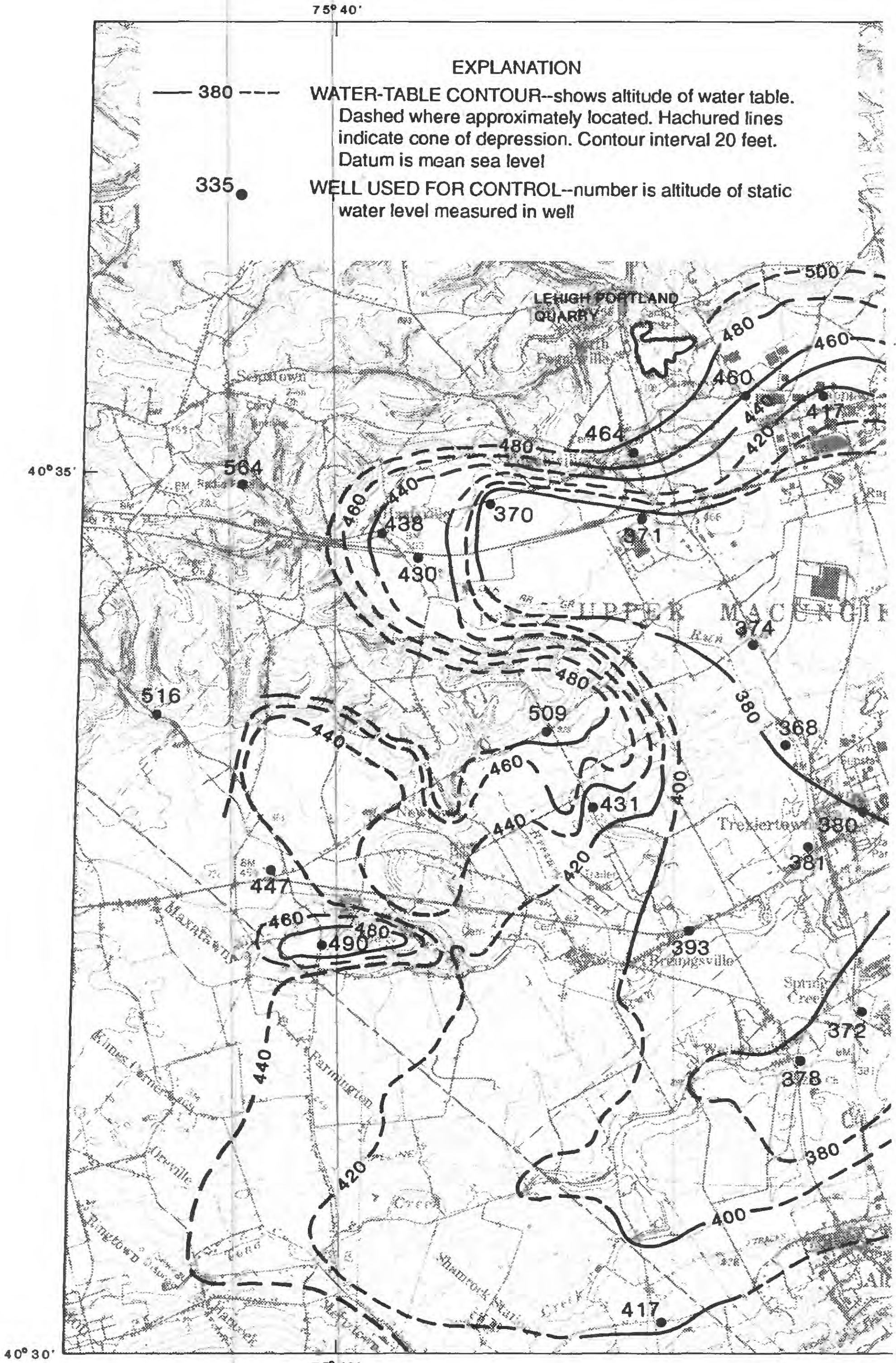


Figure 8.--Streamflow and base-flow hydrographs of Little Lehigh Creek near Allentown, 1965 and 1984.



Base from U.S. Geological Survey

Berks County 1:50,000, 1978
Lehigh County 1:50,000, 1988

MN
GN
10°
178 MILS
0° 02'
1 MIL

UTM GRID AND 1966 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

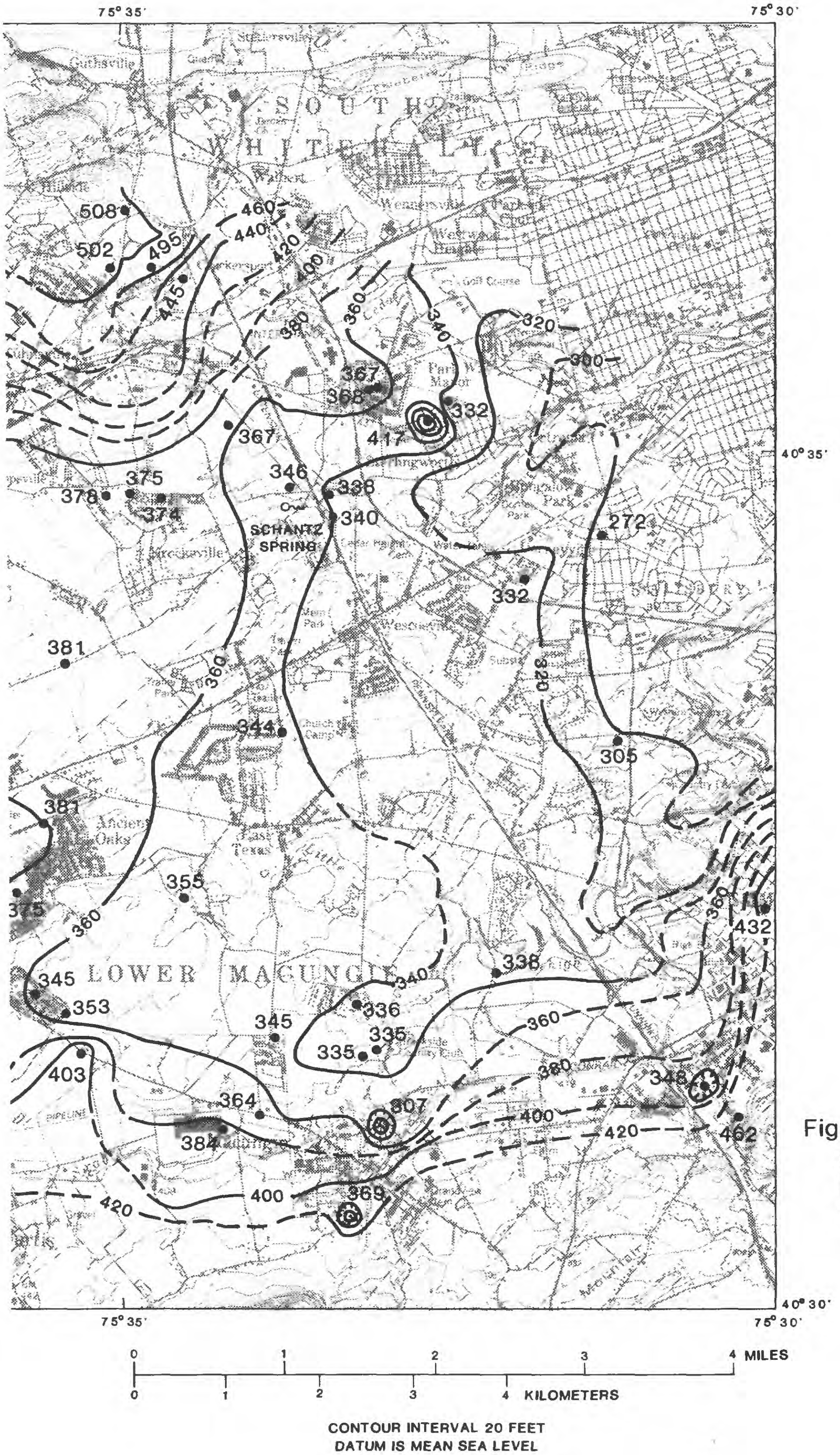


Figure 9.--Water-level contours of Upper Macungie and Lower Macungie Townships, 1984.

Ground-water divides and surface-water divides do not coincide in the carbonate rocks of the Little Lehigh Creek basin. Wood and others (1972, p. 20) estimated from the location of ground-water divides on the 1968 water-table map that the ground-water basin contributing most of the streamflow measured at the streamflow gage on Little Lehigh Creek near Allentown (station 01451500) was 10.5 mi^2 smaller than the surface-water basin. Because ground-water divides and surface-water divides do not coincide, underflow of ground water occurs from the Little Lehigh Creek basin above the gaging station to adjoining surface-water basins.

Wood and others (1972, p. 20) estimated that ground water from 2.7 mi^2 of the Little Lehigh Creek surface-water basin above gaging station 01451500 flowed to the Lehigh Portland quarry because of the cone of depression caused by quarry dewatering. During the 1960's, the Lehigh Portland quarry, located near the boundary between the Little Lehigh and Jordan Creek basins, pumped as much as 4 Mgal/d (million gallons per day). The Lehigh Portland quarry has been inactive since 1970, and the 1984 water table map (fig. 9) does not show a cone of depression around the quarry. Thus, the Little Lehigh Creek ground-water basin is 2.7 mi^2 larger than it was in the 1960's.

Wood and others (1972, p. 21) estimated that 8.25 mi^2 of the 10.4 mi^2 Schantz Spring ground-water basin (as delineated by Wood and others, 1972, plate 1) underlies the Little Lehigh Creek surface-water basin above streamflow-gaging station 01451500, and underflow occurs from the Little Lehigh Creek surface-water basin to the Schantz Spring basin. Schantz Spring discharges to the Cedar Creek surface-water basin, and underflow from the Little Lehigh Creek basin increases the base flow of Cedar Creek. Wood and others (1972, p. 18) calculated that average underflow plus diversions from the Little Lehigh Creek surface-water basin above streamflow-gaging station 01451500 was 2.6 in/yr for 1946-62. The 1984 water-table map (fig. 9) shows that the ground-water divide between the Little Lehigh Creek and Schantz Spring ground-water basins is at nearly the same location as the divide on the 1968 water-table map (Wood and others, 1972, pls. 1 and 4A).

The installation of a new streamflow-gaging station in 1986 on Little Lehigh Creek just below the confluence with Cedar Creek permits an approximate calculation of underflow between the Little Lehigh Creek and Cedar Creek basins. The newer downstream gaging station, Little Lehigh Creek at 10th Street Bridge, Allentown (station number 01451650) and the older upstream gaging station, Little Lehigh Creek near Allentown (01451500) are shown on figure 10. Gaging station 01451500 measures the discharge from 80.8 mi^2 of the Little Lehigh Creek basin above the confluence with Cedar Creek. Gaging station 01451650 measures the discharge from 98.2 mi^2 of the Little Lehigh Creek basin. Subtracting the discharge at 01451500 from 01451650 gives the discharge from the entire 15 mi^2 Cedar Creek basin and 2.4 mi^2 of the Little Lehigh Creek basin below gaging station 01451500. The city of Allentown pumps water for public supply from Little Lehigh Creek above gaging station 01451650. Daily diversions by the city of Allentown were added to the mean daily discharge measured at gaging station 01451650 to create streamflow record without the diversion. The revised hydrograph was separated into base-flow and overland-runoff components using hydrograph-separation techniques (Sloto, 1991). The city of Allentown diverts most of the flow from Schantz Spring that otherwise would discharge to Cedar Creek and most of the

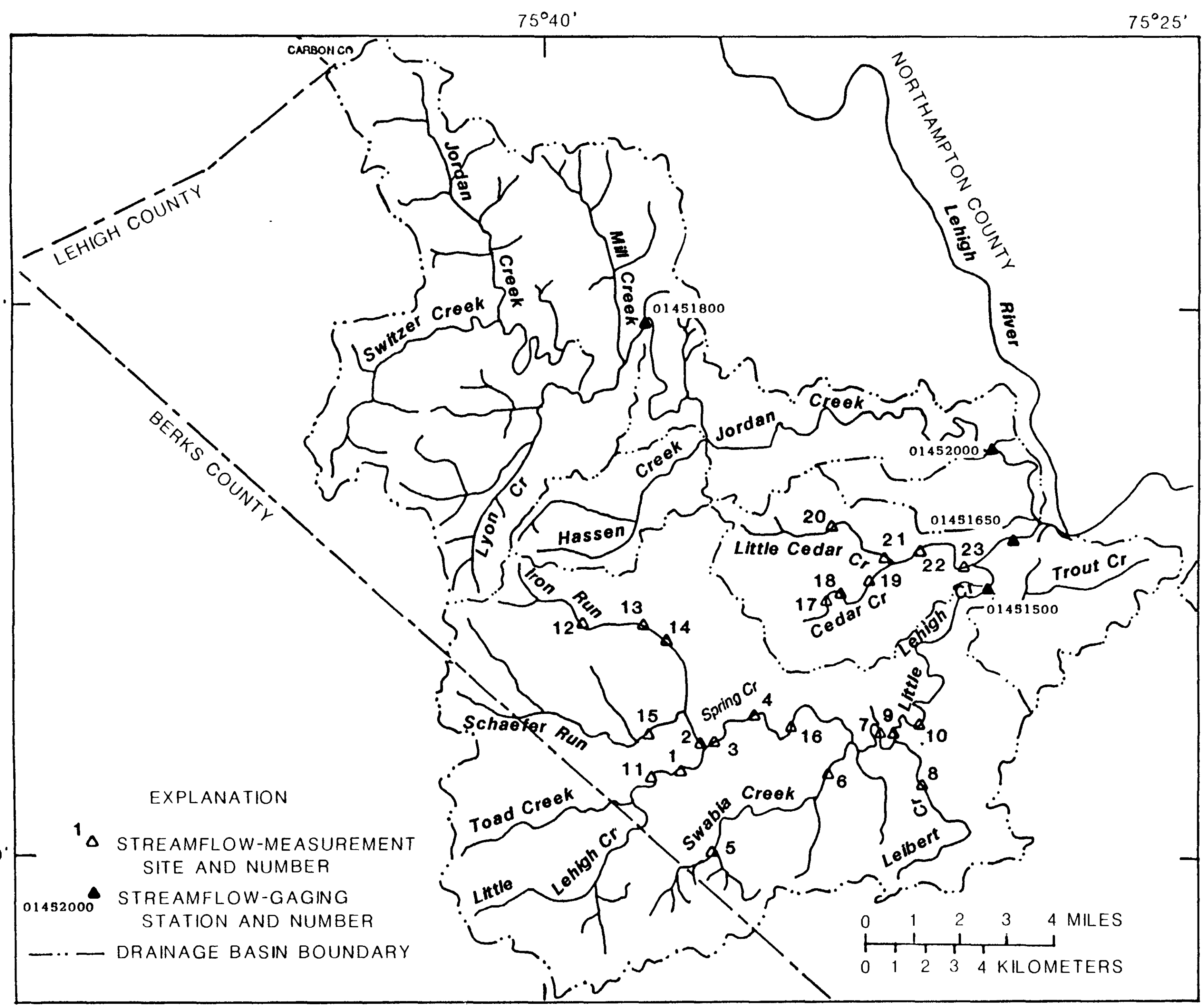


Figure 10.--Location of streamflow-measurement sites in the Little Lehigh Creek basin.

flow from Crystal Spring that otherwise would discharge to Little Lehigh Creek just above gaging station 01451650. The Schantz Spring and Crystal Spring diversions and ground-water withdrawals are added to the base flow estimated at gaging station 01451650 in order to calculate the total ground-water discharge from the Little Lehigh Creek basin above the gaging station 01451650.

Assumptions for the underflow calculation are that recharge and ground-water discharge (base flow) are equal over the area of each basin and underflow only occurs between the Little Lehigh Creek basin above gaging station 01451500 and the Cedar Creek basin. The assumption of equal recharge and base flow is supported by similar physical characteristics (geology, topography, and precipitation) of each basin. The actual distribution of ground-water discharge over the basins is unknown. In reality, it probably varies both spatially and temporally. The assumption of no net underflow to other basins is supported by the 1984 water-table map, which shows a ground-water divide very near the western boundary of the Little Lehigh surface-water basin. Ground-water divides are coincident with surface-water divides in noncarbonate rocks to the north and south.

The total volume of ground-water discharge from the basin above gaging station 01451650 is calculated by

$$V_t = D_s + BF_t + GW_t, \qquad (1)$$

where V_t = total volume of ground-water discharge,

D_s = diversions from Schantz and Crystal Springs,

BF_t = estimated base flow at gaging station 01451650, and

GW_t = ground-water withdrawals from the basin above gaging station 01451650 exported from the basin.

For 1987,

$$V_t = 5.7 \times 10^8 \text{ ft}^3 + 3.60 \times 10^9 \text{ ft}^3 + 3.68 \times 10^8 \text{ ft}^3 = 4.54 \times 10^9 \text{ ft}^3$$

The total volume of ground-water discharge (V_t) is divided by the drainage area (DA_t) at gaging station 01451650 to calculate the volume of ground-water discharge per square mile (V_{sm}):

$$V_{sm} = \frac{V_t}{DA_t} = \frac{4.54 \times 10^9 \text{ ft}^3}{98.2 \text{ mi}^2} = 4.62 \times 10^7 \text{ ft}^3/\text{mi}^2 \qquad (2)$$

Therefore, the volume of ground-water discharge per square mile (V_{sm}) from Little Lehigh Creek basin above gaging station 01451650 is 4.62×10^7 ft³/mi² (cubic feet per square mile). Assuming equal ground-water discharge to Little Lehigh Creek everywhere in the basin, the theoretical volume of ground-water discharge from the 80.8-mi² drainage area above gaging station 01451500 (V_1) would be equal to the volume of ground-water discharge per square mile (V_{sm}) multiplied by the drainage area of the basin above gaging station 01451500 (DA_1):

$$V_1 = V_{sm} \times DA_1 = 4.62 \times 10^7 \text{ ft}^3/\text{mi}^2 \times 80.8 \text{ mi}^2 = 3.73 \times 10^9 \text{ ft}^3 \qquad (3)$$

The actual base flow from the 80.8-mi^2 basin above gaging station 01451500 (BF_1) was estimated using hydrograph-separation techniques (Sloto, 1991). Underflow (U) is then calculated by subtracting the sum of the base flow plus ground-water withdrawals (GW_1) from the theoretical discharge to the basin (V_1) above gaging station 01451500:

$$U = V_1 - (BF_1 + GW_1) \qquad (4)$$
$$U = 3.73 \times 10^9 \text{ ft}^3 - (2.71 \times 10^9 \text{ ft}^3 + 2.72 \times 10^8 \text{ ft}^3)$$
$$U = 7.48 \times 10^8 \text{ ft}^3 = 3.98 \text{ in/yr.}$$

Underflow from the Little Lehigh Creek basin above streamflow-gaging station 01451500 to the Cedar Creek basin is, therefore, calculated to be 3.98 in. for 1987. This is in fair agreement with an underflow of 2.6 in/yr estimated by Wood and others (1972, p. 18). Underflow from the Little Lehigh Creek basin to the Cedar Creek basin is not constant and depends on antecedent conditions, recharge, and stresses applied to the system. The base flow of Little Lehigh Creek at gaging station 01451500 in 1987 (14.44 in.) is only slightly less than the 1975-83 average (14.75 in.); therefore, an underflow of about 4 in/yr is probably representative of the average underflow.

When the altitude of the water table is above the altitude of the stream surface, ground water discharges to the stream and the stream gains water. As the altitude of the water table increases above the altitude of the stream surface, ground-water discharge to the stream increases. When the altitude of the water table is below the altitude of the stream surface, the stream loses water to the ground-water system. The quantity of streamflow lost is controlled by the vertical hydraulic conductivity of the stream-bottom material, the cross-sectional area of the stream bottom, and the difference between the head in the aquifer and the stream surface when the head in the aquifer is above the streambed or stream depth when the water table is below the stream bottom.

In the western part of the Little Lehigh Creek basin, some streams, particularly the upper reaches of Iron Run, Schaefer Run, and Toad Creek, lose water to the ground-water system. Here the water table is usually several feet to tens of feet below the bottom of streams. When the water table falls below the stream surface, a gaining stream reach becomes a losing reach. In some areas, such as the lower reach of Spring Creek near Trexlertown and the reach of Little Lehigh Creek between Route 100 and East Texas, the carbonate rocks are permeable enough to accept and transmit all available base flow when the altitude of the water table is below the altitude of the stream bed. Streams in the Little Lehigh Creek basin can have both gaining and losing reaches in close proximity. All streamflow lost in the upper part of the basin eventually returns to the stream as ground-water discharge to gaining reaches in the lower part of the basin, generally downstream from the confluence with Swabia Creek (Wood and others, 1972, p. 127).

Seepage investigations were conducted on Little Lehigh and Cedar Creeks to determine gaining and losing reaches. Streamflow measurement sites are shown on figure 10. Seepage measurements on Little Lehigh Creek were made on May 1, 1985 (table 5), December 4, 1985 (table 6), and May 2, 1986 (table 7). Seepage measurements were made on Cedar Creek on September 11, 1986 (table 8).

Table 5.--Discharge measured during seepage investigation of Little Lehigh Creek, May 1, 1985
[Sites are shown on figure 10; --, no data]

Site number	Stream, location, and latitude-longitude	Discharge (cubic feet per second)		Gain or loss and(or) measurement error	
		Tributary	Main stream	Segment	Cumulative
1	Little Lehigh Creek at Weilersville, 200 feet upstream from bridge on Spring Creek Road (403135 0753635)	--	11.70	--	--
2	Spring Creek at Route 100, downstream from bridge (403202 0753603)	7.64	--	--	--
3	Little Lehigh Creek below Route 100, below confluence with Spring Creek (403207 0753549)	--	14.9	3.2	3.2
4	Little Lehigh Creek near Ancient Oaks, 200 feet downstream from bridge (403236 0753444)	--	13.0	-1.9	1.3
5	Swabia Creek above Alburtis, 100 feet upstream from Main Street bridge (403006 0753553)	2.03	--	--	--
6	Swabia Creek below Macungie, 50 feet upstream from Brookside Road bridge (403135 0753259)	2.60	--	.57	--
7	Little Lehigh Creek above turnpike bridge, 0.33 miles upstream from turnpike bridge (403216 0753141)	--	15.5	2.5	3.8
8	Leiberts Creek at Emmaus, 200 feet downstream from Shimerville Road bridge (403217 0753123)	1.35	--	--	--
9	Little Lehigh Creek above Route 29, 1,200 feet upstream from Route 29 bridge (403117 0753031)	--	22.3	6.8	10.6
10	Little Lehigh Creek at Emmaus, 210 feet downstream from Orchard Street bridge (403229 0753042)	--	24.6	2.3	12.9
01451500	Little Lehigh Creek near Allentown at gaging station	--	[1]45.3	20.7	33.6

[1] Discharge from stage and rating table.

The seepage investigations show that losing reaches can become gaining reaches. On May 1, 1985, the reach of Little Lehigh Creek between Weilersville (4031350753635) and Ancient Oaks (4032360753444) lost 6.3 ft³/s. The reach from below the confluence with Spring Creek (4032070753549) to Ancient Oaks lost 1.9 ft³/s. On December 4, 1985, the reach between Weilersville to Ancient Oaks gained 18.6 ft³/s. The reach from below the confluence with Spring Creek to Ancient Oaks gained 2.7 ft³/s. On May 2, 1986, the reach between Weilersville and below the confluence with Spring Creek gained 1.7 ft³/s.

Median ground-water temperatures measured by Wood and others (1972, p. 120) were 11 to 12 °C (degrees Celsius). Surface-water-temperature measurements made during the May 2, 1986, seepage investigation (table 7) are an indicator of ground-water discharge. Higher water temperatures (14.5 to

Table 6.--Discharge measured during seepage investigation of Little Lehigh Creek, December 4, 1985
[Sites are shown on figure 10; --, no data]

Site number	Stream, location, and latitude-longitude	Discharge (cubic feet per second) Main stream	Gain or loss and(or) measurement error Segment	Cumulative
1	Little Lehigh Creek at Weilersville, 150 feet upstream from bridge on Spring Creek Road (403135 0753635)	47.3	--	--
3	Little Lehigh Creek below Route 100, 300 feet below confluence with Spring Creek (403207 0753549)	63.2	15.9	15.9
4	Little Lehigh Creek near Ancient Oaks, 20 feet downstream from farm bridge (403236 0753444)	65.9	2.7	18.6
10	Little Lehigh Creek at Emmaus, 100 feet upstream from Orchard Street bridge (403229 0753042)	82.4	16.5	35.1
01451500	Little Lehigh Creek near Allentown at gaging station	[1] 125	42.6	77.7

[1] Discharge from stage and rating table.

18 °C) indicate that streamflow is mainly surface runoff. Lower water temperatures (11 to 12 °C) indicate that streamflow is mainly ground-water discharge.

The seepage investigation conducted on Cedar Creek on September 11, 1986 (table 8), showed that Cedar Creek gained water at all measurement sites.

Geology is a major factor in ground-water/surface-water relations and streamflow characteristics. Streams flowing over noncarbonate rock are generally gaining streams; streams flowing over carbonate rock can have gaining and losing reaches, depending on the altitude of the water table. Streamflow characteristics at three gaging stations in the Little Lehigh Creek basin were compared to show the effect of geology on streamflow. Little Lehigh Creek above the gaging station near Allentown (station number 01451500) drains primarily carbonate rock. Jordan Creek above the gaging station near Schnecksville (station number 01451800) drains primarily noncarbonate rock, Jordan Creek above the gaging station at Allentown (station number 01452000) drains both carbonate and noncarbonate rock, and Jordan Creek between the Schnecksville and Allentown gaging stations drains primarily carbonate rock. The drainage areas at the gaging stations are 80.8, 53.0, and 75.8 mi^2, respectively. The drainage area of Jordan Creek between the Schnecksville and Allentown gaging stations is 22.8 mi^2. A common period of record, 1967-86, was used for the following analysis. The discharge of Jordan Creek between the Schnecksville and Allentown gaging stations was determined by subtracting the mean daily discharge at the Schnecksville gaging station from the mean daily discharge at the Allentown gaging station. When the difference in flow was less than zero, indicating a net loss of water in this reach, streamflow

Table 7.--Discharge and water temperature measured during seepage investigation of Little Lehigh Creek, May 2, 1986
[Sites are shown on figure 10; --, no data]

Site number	Stream, location, and latitude-longitude	Discharge (cubic feet per second) Tributary	Main stream	Gain or loss and(or) measurement error Segment	Cumulative	Stream temperature (degrees Celsius)
11	Little Lehigh Creek above Weilersville, 5 feet downstream from bridge (403133 0753723)	--	22.6	--	--	16.0
1	Little Lehigh Creek at Weilersville, 200 feet upstream from bridge on Spring Creek Road (403135 0753635)	--	26.3	3.7	3.7	--
12	Iron Run at Bull Frog Road, 100 feet downstream from Bull Frog Road bridge (403415 0753913)	--	--	--	--	15.0
13	Iron Run at Schantz Spring Road between Bull Frog and Schantz Spring Roads (403412 0753742)	--	--	--	--	17.0
14	Iron Run below Grim Road, 30 feet downstream from bridge (403357 0753705)	--	--	--	--	17.0
15	Schaefer Run downstream from intersection of Route 222 and Old Breinigsville Highway (403223 0753725)	--	--	--	--	18.0
2	Spring Creek at Route 100 downstream from bridge (403202 0753603)	29.6	--	--	--	14.5
3	Little Lehigh Creek below Route 100, below confluence with Spring Creek (403207 0753549)	--	57.6	31.3	35.0	--
4	Little Lehigh Creek near Ancient Oaks, 200 feet downstream from farm bridge (403236 0753444)	--	54.7	-2.9	32.1	12.0
16	Little Lehigh Creek near East Texas, below bridge on Willow Lane (403221 0753352)	--	65.9	11.2	43.3	11.0
6	Swabia Creek below Macungie, 50 feet upstream from Brookside Road bridge (403135 0753259)	13.4	--	--	--	11.0
7	Little Lehigh Creek above turnpike bridge, 0.33 miles upstream from turnpike bridge (403216 0753141)	--	95.6	29.7	73.0	11.5
01451500	Little Lehigh Creek near Allentown at gaging station	--	[1] 117	21.4	94.4	--

[1] Discharge from stage and rating table.

was set equal to zero. During 1967-86, the difference in flow between the gaging stations was less than zero on 559 days or 8 percent of the time. Base flow was estimated by hydrograph separation (local-minimum technique) using the computer program of Sloto (1991).

Streams that drain carbonate rock have lower streamflow, a lower percentage of overland runoff, and a more sustained base flow. The streamflow frequency distribution (fig. 11), base-flow frequency distribution (fig. 12), and summary (table 9) are given in inches so that the different-size drainage basins can be compared. Little Lehigh Creek, which drains primarily carbonate rock, has lower streamflow (fig. 11), higher base flow (fig. 12), a lower percentage of streamflow as overland runoff, and a greater percentage of

Table 8.--Discharge and water temperature measured during seepage investigation of Cedar Creek, September 11, 1986
[Sites are shown on figure 10; --, no data]

Site number	Stream, location, and latitude-longitude	Discharge (cubic feet per second) Tributary	Main stream	Gain or loss and(or) measurement error: Segment	Cumulative	Stream temperature (degrees Celsius)
17	Cedar Creek, 1,000 feet below Schantz Spring, 100 feet below bridge (403440 0753303)	--	1.03	--	--	14.0
18	Cedar Creek, 100 feet below bridge near County Home (403442 0753235)	--	2.29	1.26	1.26	13.0
19	Cedar Creek, 25 feet above bridge on Main Blvd. (403500 0753153)	--	10.3	8.0	9.3	13.5
20	Little Cedar Creek, bridge at west end of golf course (403602 0753250)	Dry	--	--	--	--
21	Little Cedar Creek, 35 feet above bridge in southern Trexler Memorial Park (403524 0753136)	2.10	--	2.10	--	17.5
22	Cedar Creek, 15 feet above central bridge in Cedar Creek Park (403537 0753045)	--	14.7	4.4	13.7	16.0
23	Cedar Creek, 1,500 feet above confluence with Little Lehigh Creek (403515 0752942)	--	15.3	.6	14.3	17.0

streamflow as base flow (table 9) than does Jordan Creek near Schnecksville, which drains primarily noncarbonate rock. Jordan Creek near Schnecksville has a higher streamflow (fig. 11) than the other stream reaches.

Jordan Creek between the Schnecksville and Allentown gaging stations, which drains primarily carbonate rock, has the lowest base flow of all the stations (fig. 12) and lower streamflow (fig. 11) than Jordan Creek near Schnecksville. In the reach between Schnecksville and Allentown, Jordan Creek loses large quantities of streamflow to the ground-water system. Wood and others (1972, p. 142) estimated that Jordan Creek goes completely dry in this reach about once every 2 years. Streamflow loss in this reach is related to ground-water levels and was described by Wood and others (1972, p. 142-154). Some of the streamflow lost in this reach becomes ground-water underflow from the Jordan Creek basin to the Lehigh River.

Table 9.--Average streamflow and base flow of Little Lehigh and Jordan Creeks, 1967-86

[mi^2, square miles]

Gaging station	Predominant type of rock	Drainage area (mi^2)	Average streamflow (inches)	Average base flow (inches)	Percent of streamflow as base flow
Little Lehigh Creek near Allentown	carbonate	80.8	18.81	14.70	78.1
Jordan Creek near Schnecksville	noncarbonate	53.0	24.00	11.92	49.7
Jordan Creek at Allentown	carbonate and noncarbonate	75.8	22.04	11.03	50.0
Jordan Creek between Schnecksville and Allentown gages	carbonate	22.8	17.47	8.98	51.4

Water Budget

A water budget is an estimate of the quantity of water entering and leaving an area for a given period of time. The water budget balances water entering the area as precipitation with water leaving as streamflow, exported water, and evapotranspiration, taking into account any changes in storage. The water budget can be expressed as

$$P = SF + U + DIV + DS + ET, \qquad (5)$$

where P = precipitation,
SF = streamflow,
U = underflow,
DIV = diversions exported from the basin,
DS = change in ground-water storage, and
ET = evapotranspiration.

Water budgets for 1975-83 and the average budget for those years are presented for the 80.8-mi^2 part of the Little Lehigh Creek basin above gaging station 01451500 (table 10). The average water budget for 1975-83 is not a long-term average because the period spans only 9 years; however, this period can be used to approximate long-term conditions. Soil moisture generally is at field capacity in the winter. The period for the water budget begins and ends in winter; therefore, the change in soil moisture is assumed to be negligible and a soil-moisture term is not included in equation 5. Water-level records from continuous-record observation wells BE-623 and LE-860 were used to estimate the annual change in ground-water storage. Information on diversions was supplied by the Pennsylvania Department of Environmental Resources, the Lehigh County Authority, the City of Allentown Water Department, water purveyors in South Whitehall Township, and the boroughs of Emmaus, Macungie, and Topton. Precipitation is from the National Weather Service station at the Allentown-Bethlehem-Easton Airport near Allentown. Underflow is a constant; it is the average value estimated using data for 1987. Evapotranspiration is the unknown term for which equation 5 is solved. Errors in the other terms of the water-budget equation are included in the evapotranspiration term.

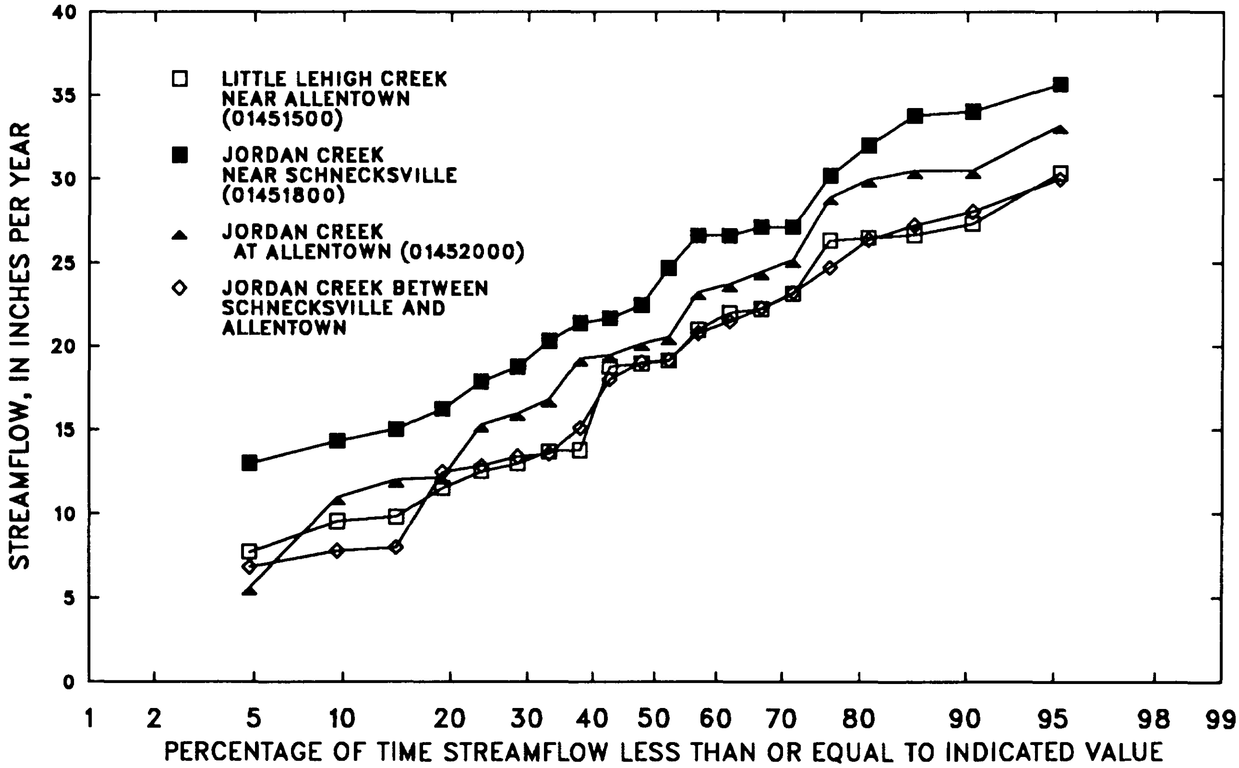


Figure 11.--Frequency distribution of streamflow, Little Lehigh and Jordan Creeks, 1967-86.

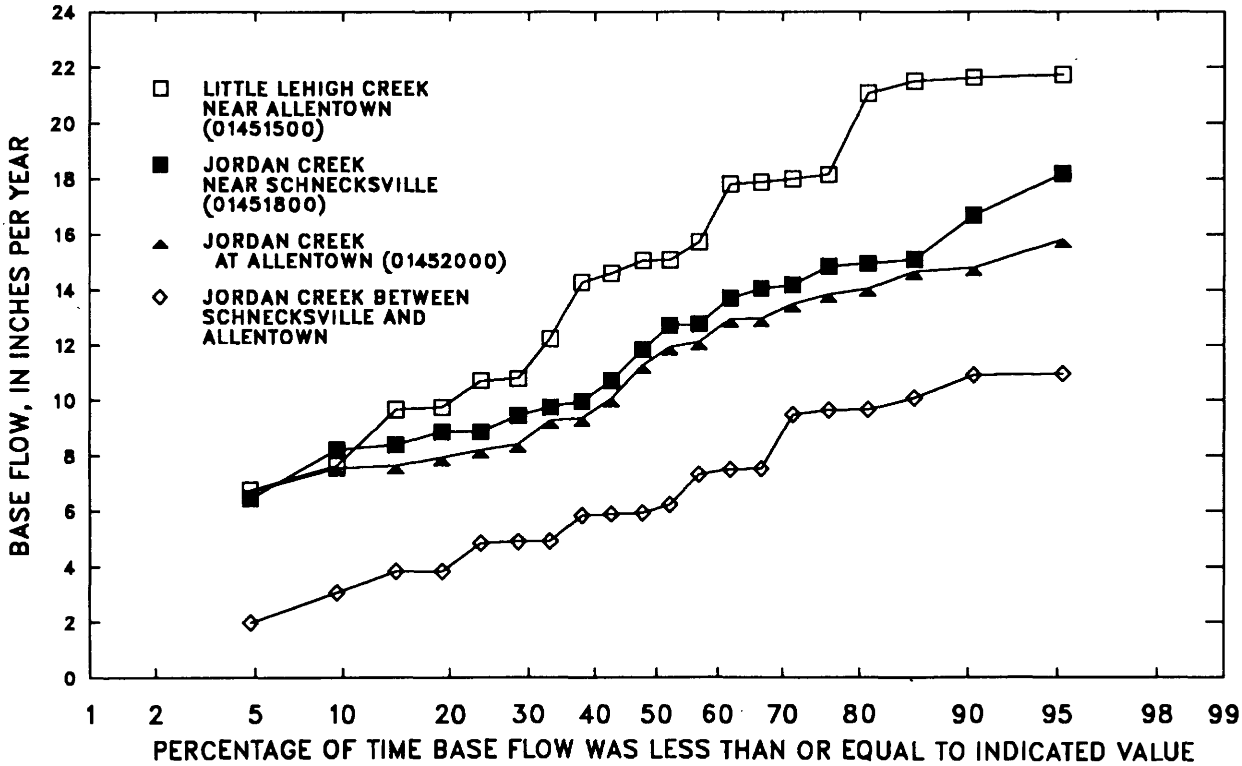


Figure 12.--Frequency distribution of base flow, Little Lehigh and Jordan Creeks, 1967-86.

Table 10.--Water budgets for the Little Lehigh Creek basin, 1975-83
[Units are in inches per year]

Year	Precip-itation	Stream-flow	Underflow	Diversions	Change in ground-water storage	Evapo-transpiration
1975	55.54	26.64	4.00	0.93	2.05	21.92
1976	39.90	18.94	4.00	1.22	-4.04	19.78
1977	49.60	19.20	4.00	1.23	4.36	20.81
1978	45.99	23.17	4.00	1.31	-3.87	21.38
1979	49.71	26.49	4.00	1.29	1.46	16.47
1980	29.83	13.85	4.00	1.45	-3.74	14.27
1981	35.08	7.75	4.00	1.38	-1.04	22.99
1982	43.40	13.71	4.00	1.42	1.65	22.62
1983	52.70	22.07	4.00	1.49	4.61	20.53
Average	44.64	19.09	4.00	1.30	.16	20.09

The annual water-level changes in wells BE-623 and LE-860 were averaged to calculate annual change in ground-water storage. The annual water-level change was calculated by subtracting the water level on December 31 from the water level on January 1. The average annual water-level change was multiplied by a specific yield of 0.05 to estimate the change in ground-water storage.

The average annual water-level change in wells BE-623 and LE-860 is assumed to be representative of the annual water-level change in the Little Lehigh Creek basin. Well BE-623 is an unused 385-ft well drilled in the Leithsville Formation. Well LE-860 is an unused 100-ft well drilled in the Allentown Dolomite. Ideally, water levels from more than two wells should be used to calculate change in ground-water storage. However, data were available only from these two wells and well LE-644. Data from well LE-644 were not used for calculating ground-water storage because of the large range in annual water-level fluctuation, which is as much as 39.22 ft. The large annual water-level fluctuations produced very large changes in ground-water storage when a specific yield of 0.05 was used. Maximum annual water-level fluctuations for 1975-83 are 10.67 ft for BE-623 and 5.78 ft for LE-860.

The average specific yield for the carbonate rocks in the Little Lehigh Creek basin was estimated by using the following equation (Meisler, 1963, p. 32):

$$Sy = \frac{q - R}{dV}\ , \qquad (6)$$

where Sy = the average specific yield for the basin,
q = total quantity of base flow discharged from the Little Lehigh Creek basin measured at gaging station 01451500,
R = total recharge added to the ground-water system, and
dV = the change in volume of dewatered rock.

For periods with no recharge this equation becomes

$$Sy = \frac{q}{dV}\ . \qquad (7)$$

Six periods, 10 to 14 days long between August 19, 1981, and September 11, 1983, were selected for this analysis. During these periods, no precipitation or snow melt took place, and therefore, no recharge. Each period began at least 3 days after precipitation to assure that direct runoff left the basin. The change in volume of the dewatered rock (dV) was calculated by multiplying the average water-level decline in well LE-860 for a given period by the total drainage area above the gaging station. The accuracy of the calculated basin specific yield depends on how closely the water-level decline in well LE-860 approximates the water-level decline in the entire basin.

An example calculation for May 2-11, 1982, is

$$q = 7.59 \times 10^7 \text{ ft}^3 \text{ (total outflow from basin)},$$

$$dV = 0.65 \text{ ft (10-day decline in well LE-860)} \times 2.25 \times 10^9 \text{ ft}^2 \text{ (area of basin)} = 1.46 \times 10^9 \text{ ft}^3;$$

therefore,

$$Sy = \frac{7.59 \times 10^7 \text{ ft}^3}{1.46 \times 10^9 \text{ ft}^3} = 0.052.$$

The calculated specific yield of the zone of water-table fluctuation in the carbonate rocks of the Little Lehigh Creek basin ranged from 0.034 to 0.065 and averaged 0.051 or about 5 percent (table 11). Average specific yield in similar areas in Pennsylvania are 5 percent for the carbonate rocks of the Lebanon Valley (Meisler, 1963), and 4 percent for the carbonate rocks of the Lancaster Quadrangle (Meisler and Becher, 1971). Wood and others (1972, p. 111) used 4.4 percent for the carbonate rocks of the Lehigh Valley.

Underflow was estimated using data for 1987 (see section on Ground-Water/Surface-Water Relations). Because data are not available for 1975-83, the estimated 1987 average underflow was used for each year in the water budget. However, the quantity of underflow varies from year to year depending on climatic conditions and is not known for 1975-83. Use of an average underflow causes an underestimation or overestimation of annual evapotranspiration in table 10, the unknown for which equation 5 is solved. Although annual estimates of evapotranspiration in table 10 are affected by estimating underflow, the 1975-83 average evapotranspiration is probably not affected. The 1975-83 average evapotranspiration is lower than the evapotranspiration of 26.4 in. for the Little Lehigh Creek basin and 24.5 in. for the Jordan Creek basin estimated by Wood and others (1972, p. 18 and 26) for 1946-62.

Table 11.--Estimates of specific yield for the Little Lehigh Creek basin

Period	Base flow (cubic feet)	Change in water level in LE-860 (feet)	Specific yield
August 19-29, 1981	2.85×10^7	0.32	0.040
May 2-11, 1982	7.59×10^7	.65	.052
September 6-19, 1982	7.10×10^7	.54	.058
October 1-12, 1982	3.44×10^7	.45	.034
August 16-27, 1983	5.59×10^7	.38	.065
September 1-11, 1983	4.79×10^7	.37	.058
Average			.051

Recharge

Annual recharge and average recharge for 1975-83 was estimated for Little Lehigh Creek above gaging station 01451500 (table 12). The recharge rates were calculated by using the following equation:

$$R = BF + GWET + DIV + DS + U, \qquad (8)$$

where
- R = recharge,
- BF = base flow,
- GWET = ground-water evapotranspiration,
- DIV = diversions exported from the basin,
- DS = change in ground-water storage, and
- U = underflow.

Base flow was estimated by hydrograph separation (local-minimum technique) with data from Little Lehigh Creek near Allentown (station number 01451500) using the computer program of Sloto (1991). Ground-water evapotranspiration was estimated. Ground-water diversions and changes in ground-water storage were based on the basin water budgets (table 10).

Table 12.--Recharge to the Little Lehigh Creek basin, 1975-83
[Units are inches per year]

Year	Recharge	Base flow	Ground-water evapotranspiration	Diversions	Change in ground-water storage	Underflow
1975	29.98	21.50	1.50	0.93	2.05	4.00
1976	17.73	15.05	1.50	1.22	-4.04	4.00
1977	26.17	15.08	1.50	1.23	4.36	4.00
1978	20.75	17.81	1.50	1.31	-3.87	4.00
1979	26.40	18.15	1.50	1.29	1.46	4.00
1980	15.42	12.21	1.50	1.45	-3.74	4.00
1981	12.60	6.76	1.50	1.38	-1.04	4.00
1982	19.35	10.78	1.50	1.42	1.65	4.00
1983	27.31	15.71	1.50	1.49	4.61	4.00
Average	21.75	14.78	1.50	1.30	.16	4.00

Underflow was estimated using data for 1987 (see section on Ground-Water/Surface-Water Relations). Because data are not available for 1975-83, the estimated 1987 average underflow was used for each year in the water budget. The quantity of underflow varies from year to year depending on climatic conditions. Use of an average underflow causes an underestimation or overestimation of annual recharge (table 12), but probably does not affect the 1975-83 average recharge.

Estimated annual recharge for 1975-83 ranged from 12.60 to 29.98 in/yr; the average recharge was 21.75 in/yr. Base flow was equal to 54 to 86 percent of recharge; for 1975-83, the average annual base flow was 68 percent of average annual recharge.

Water-Level Fluctuations

The carbonate rocks of the Lehigh Valley form a complex, heterogeneous water-table aquifer that fluctuates in response to recharge from precipitation and discharge to pumping wells, ground-water evapotranspiration, and streams. The water table generally rises during the fall and winter when evapotranspiration is at a minimum and recharge is at a maximum; it generally declines during the spring and summer when evapotranspiration is at a maximum and recharge is at a minimum (fig. 13). Figure 13 shows the hydrographs of wells LE-644 and LE-860. Well LE-644 is a 184-ft well drilled in the Beekmantown Group close to Iron Run; LE-860 is a 100-ft well drilled in the Allentown Dolomite near Little Lehigh Creek. Hydrographs of both wells show similar patterns of annual fluctuations; however, the range of fluctuation differs considerably. The water level in well LE-644 fluctuated 56 ft during 1971-85, while the water level in well LE-860 fluctuated 12 ft during the same period. Well LE-644 is located along a losing reach of Iron Run that is often dry, and the water table is tens of feet below the stream bed. Well LE-860 is located along a reach of Little Lehigh Creek that periodically gains or loses water, depending on the altitude of the water table, which is within a few feet of land surface.

Schantz and Crystal Springs

Schantz and Crystal Springs (pl. 1) are a major source of water for the city of Allentown. From 1969-84, Schantz and Crystal Springs (LE-Sp-15 and LE-Sp-14, respectively) provided an average of 43 percent of the water supplied by the Allentown Water Department.

Schantz Spring is located near the contact between the Allentown Dolomite and the Epler Formation of the Beekmantown Group at an elevation of 340 ft. The contact is interpreted to be a shallow thrust fault that dips about 15° southeast and brings the Allentown Dolomite up over the Epler Formation (Drake, A.A., Jr., U.S. Geological Survey, oral commun., 1988). Crystal Spring is located in the Allentown Dolomite at an elevation of 265 ft.

The size of the Schantz Spring ground-water basin, in part, controls the discharge of Schantz Spring. The size of the ground-water basin changes when the ground-water divides that delineate it shift because of changes in recharge or withdrawals. Wood and others (1972, p. 21 and pl. 1) determined that the ground-water basin that drains to Schantz Spring is an elongated area of approximately 10.4 mi^2 that extends northwestward from the spring to the headwaters of Iron Run. They estimated that 8.25 mi^2 of this basin underlies the surface-water basin for Iron Run, a tributary to Little Lehigh Creek above gaging station 01451500, and that 2.15 mi^2 underlies the surface-water basin for Cedar Creek.

In the area between Schantz Spring and Iron Run, the rocks of the Beekmantown Group, especially the Epler Formation, appear to be especially susceptible to solution, and karst topography is well-developed. In this area, Kochanov (1987) mapped numerous karst features, such as sinkholes and

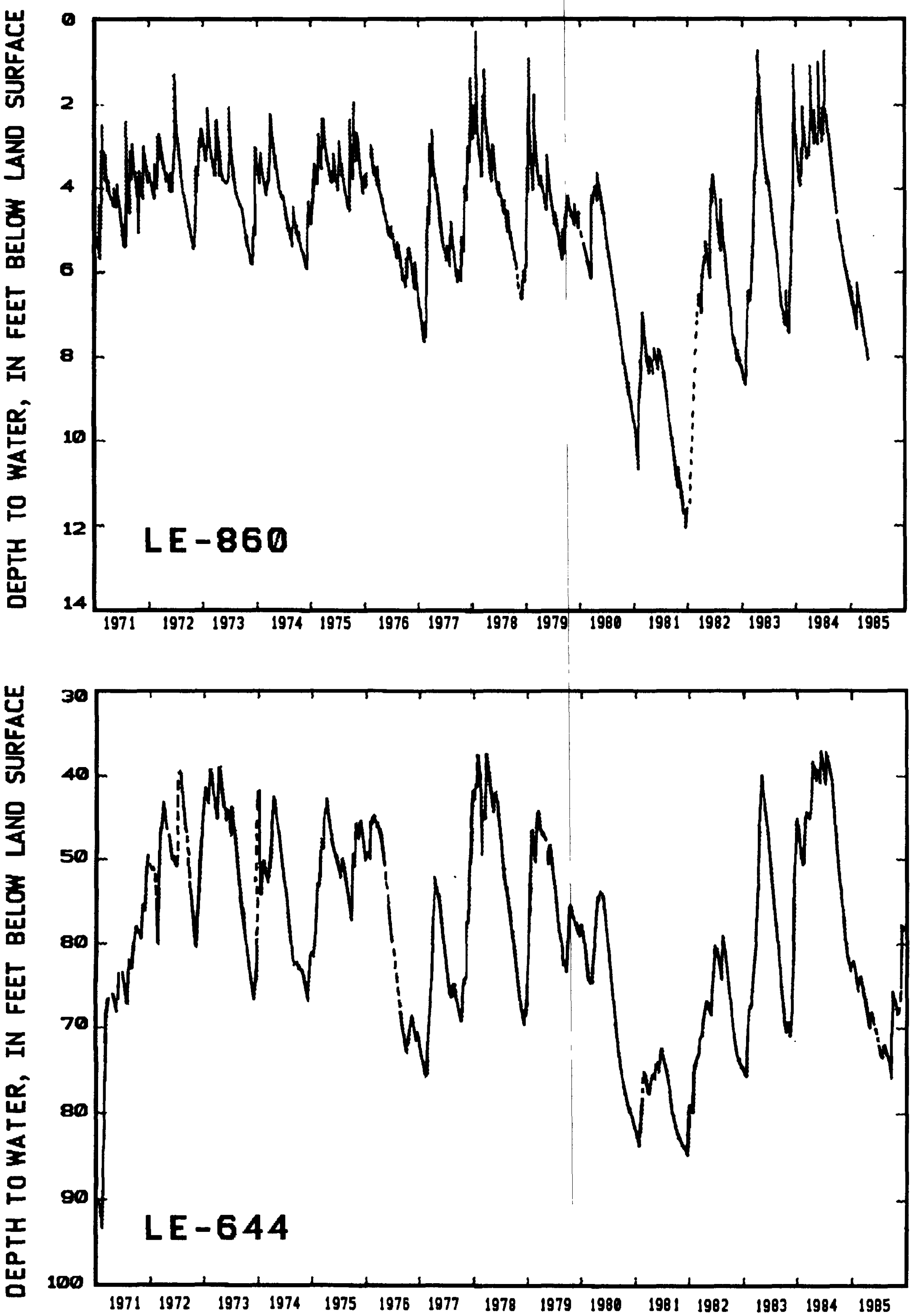


Figure 13.--Hydrographs of wells LE-644 and LE-860, 1971-85.
Line dashed where data are missing.

closed depressions. A sinkhole is a localized, gradual or rapid sinking of the land surface characterized by a roughly circular outline, a distinct breaking of the ground surface, and downward movement of soil into bedrock voids. A closed depression is a distinct bowl-shaped depression in the land surface characterized by an unbroken ground surface and internal drainage. The only streams in this area are ephemeral streams that drain into sinkholes. The lack of surface drainage indicates that recharge to this area may be enhanced.

The absence of surface drainage and the presence of well-developed karst features indicates the presence of an arterial subsurface drainage network. The outlet of this network is probably Schantz Spring, which could have developed as the result of the interruption of a main conduit of the network by the thrust fault between the Allentown Dolomite and the Beekmantown Group. Structural juxtaposition of the two geologic units could create a hydrologic barrier or the thrust fault may abruptly terminate structurally or stratigraphically controlled flow paths. The 1968 water-table map of Wood and others (1972, pl. 4a) shows a steepening of the hydraulic gradient around Schantz Spring in a pattern nearly coincident with the mapped fault, suggesting that hydraulic conductivity is reduced in the fault area. Either mechanism--structural juxtaposition or termination of preferential flow paths --could result in a reduction in hydraulic conductivity in the fault area. The steep gradient at the geologic contact also could be a damming effect at the contact between aquifers of different hydraulic conductivities. The hydraulic conductivity of the Epler Formation generally is greater than that of the Allentown Dolomite. Similar mechanisms are probably responsible for Crystal Spring.

Part of the flow from the Schantz Spring basin flows beneath the wall of the spring enclosure and discharges to Cedar Creek. Wood and others (1972, p. 22) estimated that this discharge was approximately 0.8 Mgal/d during 1968 and 1969. Wood and others (1972) also estimated an additional 0.8 Mgal/d discharged from the basin through other springs along Cedar Creek. Total estimated discharge from the Schantz Spring basin to Cedar Creek, therefore, is about 1.6 Mgal/d. This discharge probably varies roughly in proportion to the natural fluctuations in spring discharge.

Figure 14 shows the average daily discharge (1956-84) for Schantz Spring following reconstruction of the spring basin in 1954-55 and the average daily discharge (1961-84) of Crystal Spring. The average daily discharge from Schantz Spring ranged from 5.2 Mgal/d in 1966 to 8.3 Mgal/d in 1975; the average daily discharge for 1956-84 (29 years) was 6.9 Mgal/d. The average daily discharge from Crystal Spring ranged from 2.7 Mgal/d in 1981 to 5.1 Mgal/d in 1977; the average daily discharge for 1961-84 (24 years) was 4 Mgal/d (fig. 14). The flow of Schantz Spring correlates better with precipitation (Spearman correlation coefficient $r_s = 0.69$) than does the flow of Crystal Spring ($r_s = 0.40$).

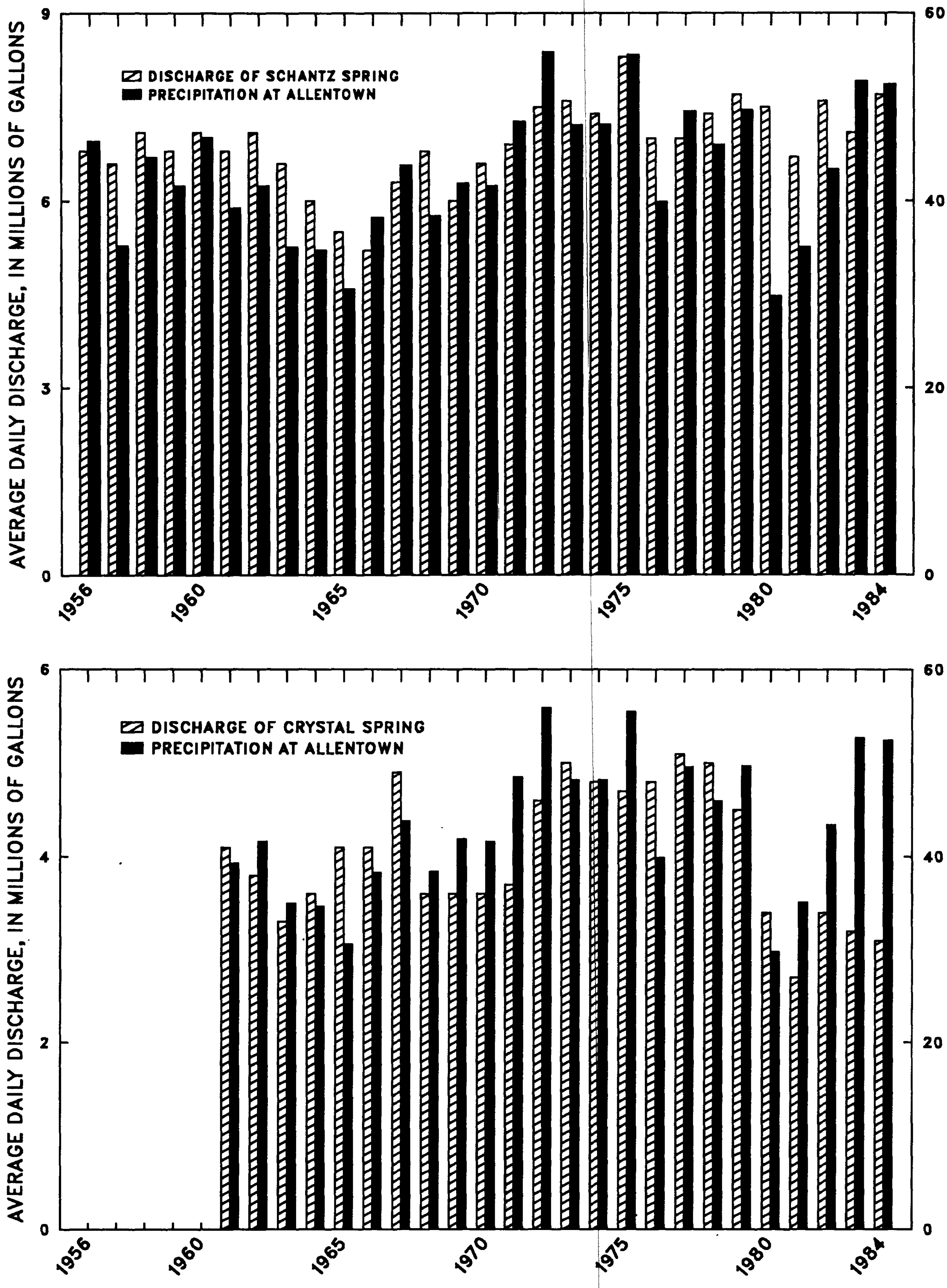


Figure 14.--Average daily discharge of Schantz and Crystal Springs and annual precipitation at Allentown, 1956-84.

Cessation of pumping from the Lehigh Portland quarry at Fogelsville and development of ground water for public supply in the Schantz Spring basin (as delineated by Wood and others, 1972, pl. 1) has not affected the flow of Schantz Spring (fig. 15). Figure 15 is a double-mass curve of the cumulative flow of Schantz Spring as a function of cumulative precipitation at Allentown for 1956-84, the period following reconstruction of Schantz Spring. The straight line indicates that no change in the constant of proportionality between the flow of Schantz Spring and precipitation occurred during 1956-84 (Searcy and Hardison, 1960, p. 33). Pumping from the Lehigh Portland Cement quarry, which averaged 6.6 Mgal/d in 1968 (Wood and others, 1972, p. 23), ceased in 1971. If cessation of pumping from the quarry caused an increase in the flow of Schantz Spring, a break in the slope of the line on figure 15 would have occurred around 1971. Ground-water pumpage in the Schantz Spring basin during the 10-year period 1975-84 increased 106 percent from 1.43 Mgal/d in 1975 to 2.94 Mgal/d in 1984. The effects of this increasing ground-water development cannot be seen in figure 15. Ground-water pumpage data from public supply in the Schantz Spring basin are not available before 1975.

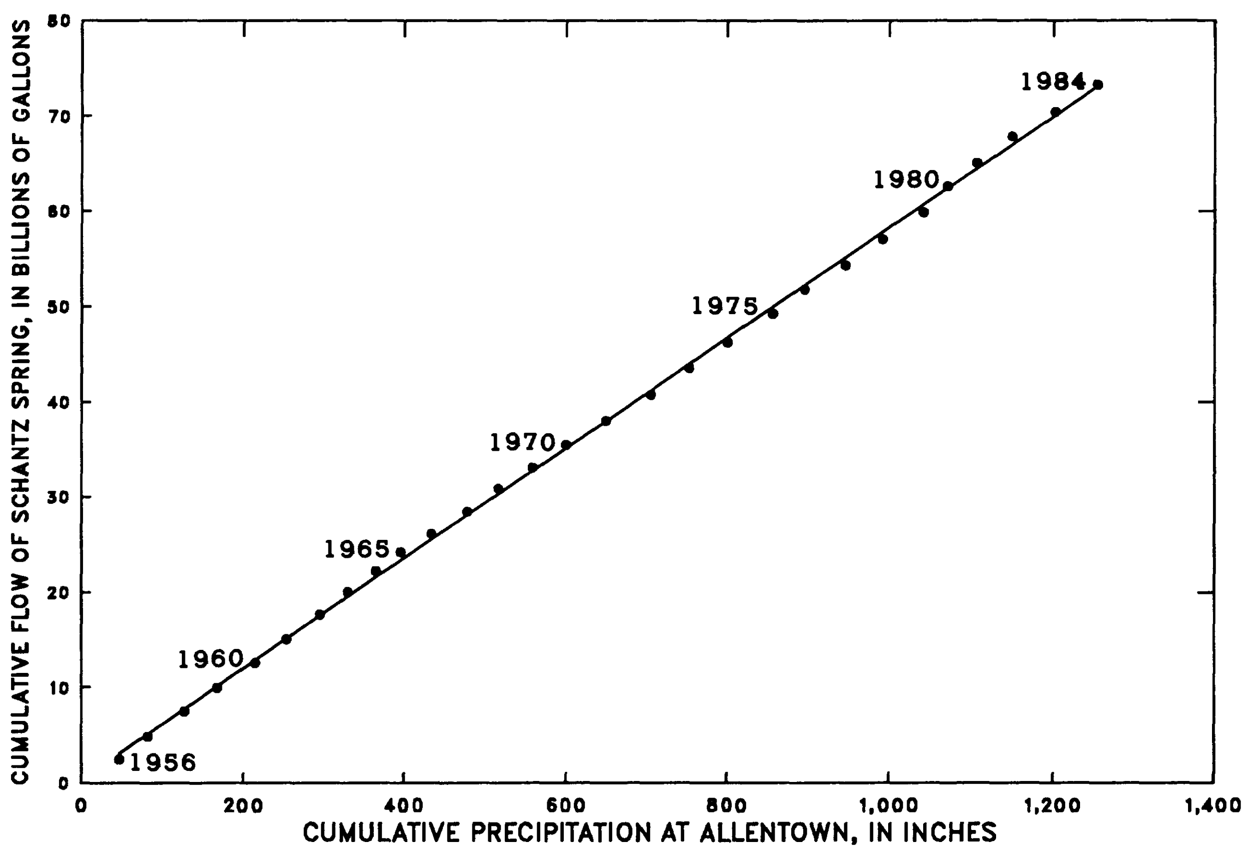


Figure 15.--Double-mass curve of the flow of Schantz Spring as a functon of precipitation at Allentown, 1956-84.

GROUND-WATER FLOW

Although the ground-water system is generally under water-table conditions, confined conditions exist locally. In carbonate rocks, ground water can be confined by the relatively impermeable sides of a fracture or solution channel. Flowing wells in the Allentown Dolomite were reported by Wood and others (1972, p. 115). However, artesian head is seldom more than a few feet above the water table.

The general direction of ground-water flow through the carbonate rocks in the Little Lehigh Creek basin is east-northeastward toward the Lehigh River. Regional flow directions and the general shape of the water table have not changed substantially since 1968. Figure 16 is part of the 1968 water-table map of Wood and others (1972, pl. 4a) for part of Upper Macungie and Lower Macungie Townships and vicinity. Figure 9 is a water-table map of the same area using water-level data collected in the summer of 1984 and supplemented with additional data collected in January 1989. Figure 9 has fewer control points than Wood and others (1972, pl. 4a) because public water suppliers have increased their distribution area and many of the domestic wells used for the 1968 map have been destroyed. The major change in the water table is the disappearance of the cone of depression around the former Lehigh Portland quarry, which ceased pumping in 1971. Except for the quarry area, the water-table maps are very similar.

No discernible vertical ground-water flow was observed in brine-trace logs run in three wells (LE-866, LE-1319, and LE-1355). As many as three brine slugs were injected at different depths into a single well and monitored for as long as 9 minutes. If vertical ground-water flow occurs, the flow is too slow to be detected by brine-tracing techniques.

Simulation of Ground-Water Flow

Ground-water flow in the carbonate rocks of the Little Lehigh Creek basin was simulated using a numerical computer model to estimate the effect of ground-water withdrawals on the base flow of Little Lehigh Creek. The model is a simplified mathematical representation of the complex hydrologic system in the basin. In order to simulate ground-water flow mathematically, certain assumptions regarding the hydrologic system were made and a simplified conceptual model developed. These are described in the following sections. The model approximates the hydrologic system within these imposed constraints and other limitations, which also are discussed below.

The effect of increased ground-water pumping on the base flow of Little Lehigh Creek was estimated using steady-state simulations. The effect of increased ground-water pumping was determined by comparing the base flow of Little Lehigh Creek with the hydrologic system in equilibrium (steady state) before new stress is applied with the base flow of Little Lehigh Creek after the hydrologic system reaches equilibrium (steady state) with the new stress. Steady-state simulations representing equilibrium conditions allow the maximum expected long-term effect of the new stress to be estimated.

Description of Flow Model

Ground-water flow was simulated using the computer program of McDonald and Harbaugh (1988). The model is a finite-difference, two-dimensional model that uses block-centered nodes. The geologic units in the modeled area were simulated as a single water-table aquifer. Recharge to, ground-water flow through, and discharge from the carbonate rocks of the Little Lehigh Creek basin were simulated.

Sources of water to the modeled carbonate rocks are areally-distributed recharge from precipitation and lateral ground-water flow from noncarbonate rocks to the north and south of the carbonate valley. Discharge of water from the modeled hydrologic system is by pumpage from wells, ground-water discharge to streams, and ground-water evapotranspiration.

Simplified Conceptual Model

Continuum methods of ground-water-flow analysis, including modeling, assume laminar flow through a medium with primary porosity and permeability (porous media). The geologic units in the Little Lehigh Creek basin have low primary porosity or permeability; ground water mainly flows through secondary openings. However, to permit analysis by continuum methods, the geologic units are assumed to approximate porous media because of the regional scale of analysis. Secondary-opening density is sufficiently great at a regional scale to permit the use of a porous-media model. A block of aquifer material is assumed to have the equivalent properties of the same-size block of porous media. The water-table map of Wood and others (1972, pl. 4a) indicates that ground-water flow is continuous on a regional scale.

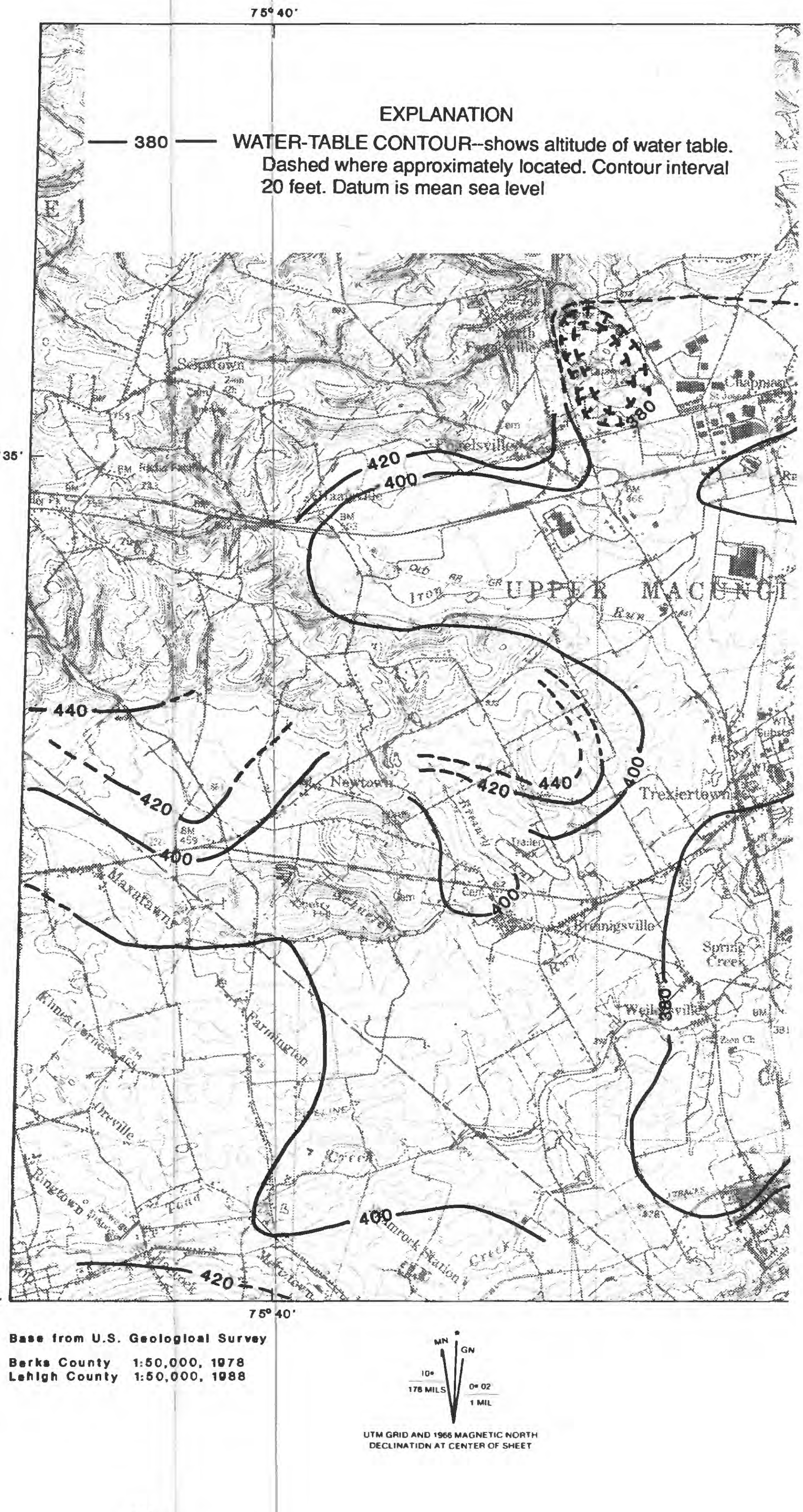
In order to analyze ground-water flow with a digital model, a simplified conceptual model of the complex physical system was developed. The conceptual model includes the following assumptions:

(1) The geologic units in the Little Lehigh Creek basin act together as a single heterogeneous water-table aquifer. Water-table maps show that the carbonate rocks behave as a single, continuous unit.

(2) A single hydraulic conductivity is specified for each geologic unit. Hydraulic properties of each geologic unit differ spatially, but are averaged for model simulation. The average is considered representative of the geologic unit.

(3) Streams are in direct hydraulic contact with the aquifer.

(4) Ground-water flow below 600 ft is considered negligible. The lower limit of ground-water flow is 600 ft below land surface based on analysis of water-bearing zones.



Base from U.S. Geological Survey
Berks County 1:50,000, 1978
Lehigh County 1:50,000, 1988

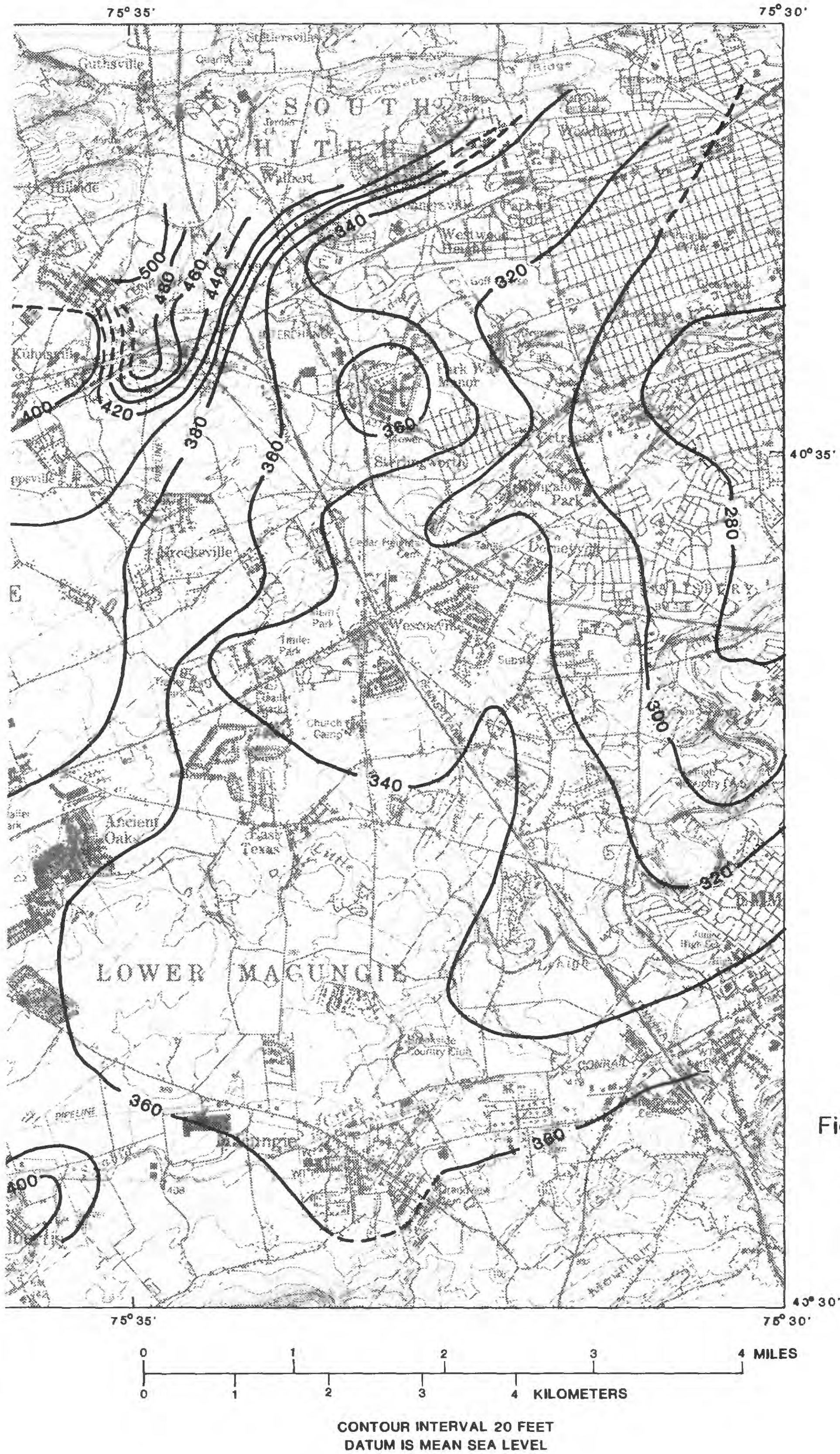


Figure 16.--Water-level contours of Upper Macungie and Lower Macungie Townships, 1968.

Discretization

Ground-water and surface-water divides do not coincide in the Lehigh Valley; therefore, the area between the Lehigh River and Sacony Creek was modeled to include the natural hydrologic boundaries of the ground-water-flow system. The modeled area was discretized into a rectangular grid of 29 rows and 45 columns containing 861 active cells (fig. 17). The cell location notation used in this report is (row, column). For example, (6, 35) denotes a cell in the 6th row and 35th column of the model grid. Cells are 2,000 ft on each side, except for columns 2, 3, and 4, which are 2,000 ft by 4,000, 4,000, and 3,000 ft, respectively. The total area covered by active cells is 134 mi^2. The carbonate rocks of the Little Lehigh Creek basin are represented by 651 active cells and have an area of 93.4 mi^2. The modeled area of the Little Lehigh Creek basin above gaging station 01451500 is 58.9 mi^2, the Cedar Creek basin is 14.6 mi^2, and the Jordan Creek basin is 18.5 mi^2. The carbonate rocks of the Coplay Creek basin are represented by 112 active cells and have an area of 16.1 mi^2. The carbonate rocks of the Sacony Creek basin are represented by 63 active cells and have an area of 12.9 mi^2. The model grid is oriented parallel to the major direction of ground-water flow, which is generally parallel to geologic contacts. Physical and hydraulic properties are averaged over the area represented by each cell and are assigned to a node in the center of the cell.

Boundary Conditions

The modeled area is defined by a set of boundary conditions. Three types of boundary conditions are used: (1) specified flux, (2) head dependent, and (3) specified head. The model program sets the conductance across the exterior faces of the cells in the first and last rows and columns of the model grid to zero; this produces a specified-flux boundary with a specified flux of zero (no-flow boundary) around the exterior cells of the grid (McDonald and Harbaugh, 1988, p. 3-14 - 3-15).

On the northwestern and southeastern sides of the modeled area, the geologic contact between the carbonate and noncarbonate rocks is a head-dependent boundary. The contact is simulated using the general-head boundary package of the McDonald and Harbaugh (1988, p. 11-1) model program. A head-dependent boundary consists of a source of water outside the modeled area (noncarbonate rock) that supplies water to a cell in the modeled area (carbonate rock) at a rate proportional to the head difference between the source and the cell. The rate at which water is supplied to the cell in the modeled area is

$$Q_h = C_h (h_s - h_a), \qquad (9)$$

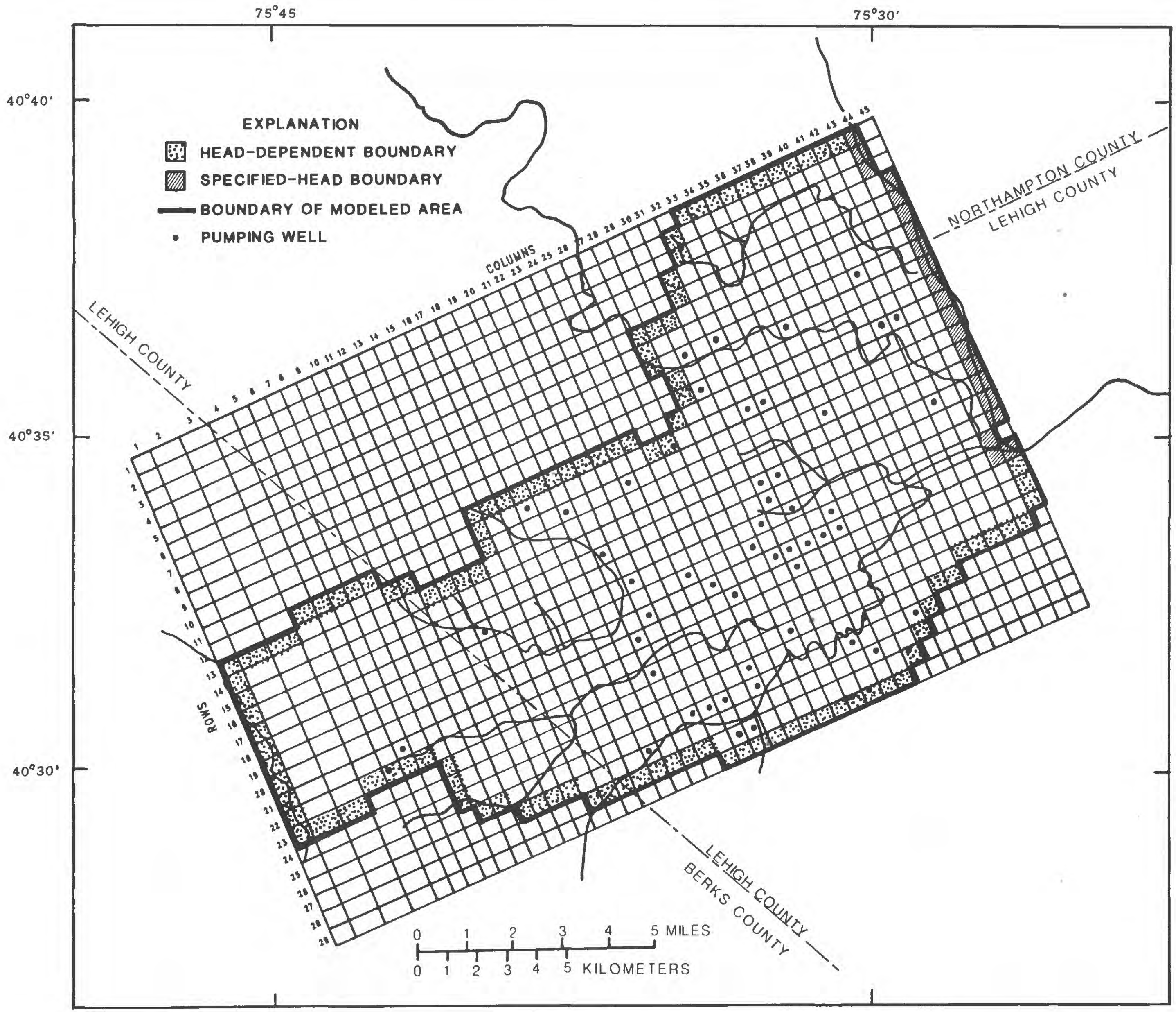


Figure 17.--Model grid and boundary conditions.

where Q_h = rate at which water enters or leaves a block along the boundary,

C_h = hydraulic conductance of the aquifer material between the known head in the source and the boundary of the simulated area,

h_s = known head in the source, and

h_a = head in the cell in the modeled area at the model boundary.

The head-dependent boundary simulates the interface between the carbonate and noncarbonate rocks. The quantity of water crossing this boundary changes as the hydraulic gradient across the boundary changes.

The hydraulic conductance for each block along the boundary is calculated by

$$C_h = K A / L, \qquad (10)$$

where
K = hydraulic conductivity,
A = the cross-sectional flow area, and
L = the flow length.

Heads in the source were taken from the 1968 water-table map (Wood and others, 1972, pl. 4a) or, in some cases, estimated. Hydraulic conductivity of the aquifer material between the head in the source area and model boundary was estimated. Estimates of hydraulic conductivity are discussed in the next section.

On the northeastern side of the modeled area, the Lehigh River is simulated as a specified-head (constant-head) boundary. The Lehigh River is a regional sink, and ground water discharges to the Lehigh River from the Lehigh Valley (Wood and others, 1972, pl. 4a).

On the southwestern side, the boundary is Sacony Creek, which is represented by a head-dependent boundary (stream cells). All streams are simulated as head-dependent boundaries. Leakage to streams (McDonald and Harbaugh, 1988, p. 6-5) is approximated by

$$Q_r = k' L W (h_r - h_a)/m, \qquad (11)$$

where
Q_r = leakage,

k' = streambed hydraulic conductivity,
L = length of stream reach,
W = width of stream,
h_r = stream stage,

h_a = head in the aquifer, and

m = streambed thickness.

The model lower boundary is a specified-flux (no-flow) boundary 600 ft below land surface. No ground-water flow crosses this boundary. The model upper boundary is represented by the water-table surface, streams, and springs. The water-table is a specified flux boundary; the flux is areal recharge. Stream cells are shown on figure 18. Schantz and Crystal Springs are simulated as drains (McDonald and Harbaugh, 1988, p. 9-3). Discharge from Schantz and Crystal Springs is calculated by

$$Q_d = C_d (h_a - h_d), \qquad (12)$$

where Q_d = rate at which water flows into the drain,

C_d = hydraulic conductance of the interface between the aquifer and the spring,

h_a = head in the aquifer near the spring, and

h_d = elevation of the spring.

Model Calibration

The ground-water-flow model of the Little Lehigh Creek basin was calibrated under steady-state conditions using average recharge, evapotranspiration, and pumping rates. The criteria used to determine when the steady-state model was calibrated included simulation of: (1) the average water budget for the Little Lehigh Creek basin above gaging station 01451500, (2) the average base flow of Little Lehigh Creek, (3) the underflow from the Little Lehigh Creek basin above gaging station 01451500 to the Cedar Creek basin, (4) head in the carbonate rocks of the Little Lehigh Creek basin, (5) regional ground-water flow, and (6) average discharge of Schantz and Crystal Springs. The model was considered calibrated when all of these criteria were met.

The recharge rate was based on the 1975-83 average recharge rate (table 12). A recharge rate of 4.97×10^{-3} ft/d (feet per day) (21.75 in/yr) was used for model simulations. Recharge from precipitation is evenly distributed over the area.

The maximum ground-water evapotranspiration (ET) rate, 4.59×10^{-3} ft/d (20.09 in/yr), was based on the 1975-83 average water budget (table 10). This rate is equal to about 70 percent of the pan evaporation rate for southeastern Pennsylvania. Ground-water ET determined by the model depends on the position of the head in the aquifer relative to two given ET reference elevations--ET surface and ET extinction depth (McDonald and Harbaugh, 1988, p. 10-1). At and above the ET surface, the ground-water ET rate is the maximum ground-water ET rate. At and below the ET extinction depth, the ground-water ET rate is zero. The ground-water ET rate varies linearly from the maximum ground-water ET rate at the ET surface to zero at the ET extinction depth. The ET surface was set to the average land-surface elevation for each cell. The ET extinction depth was set to 10 ft.

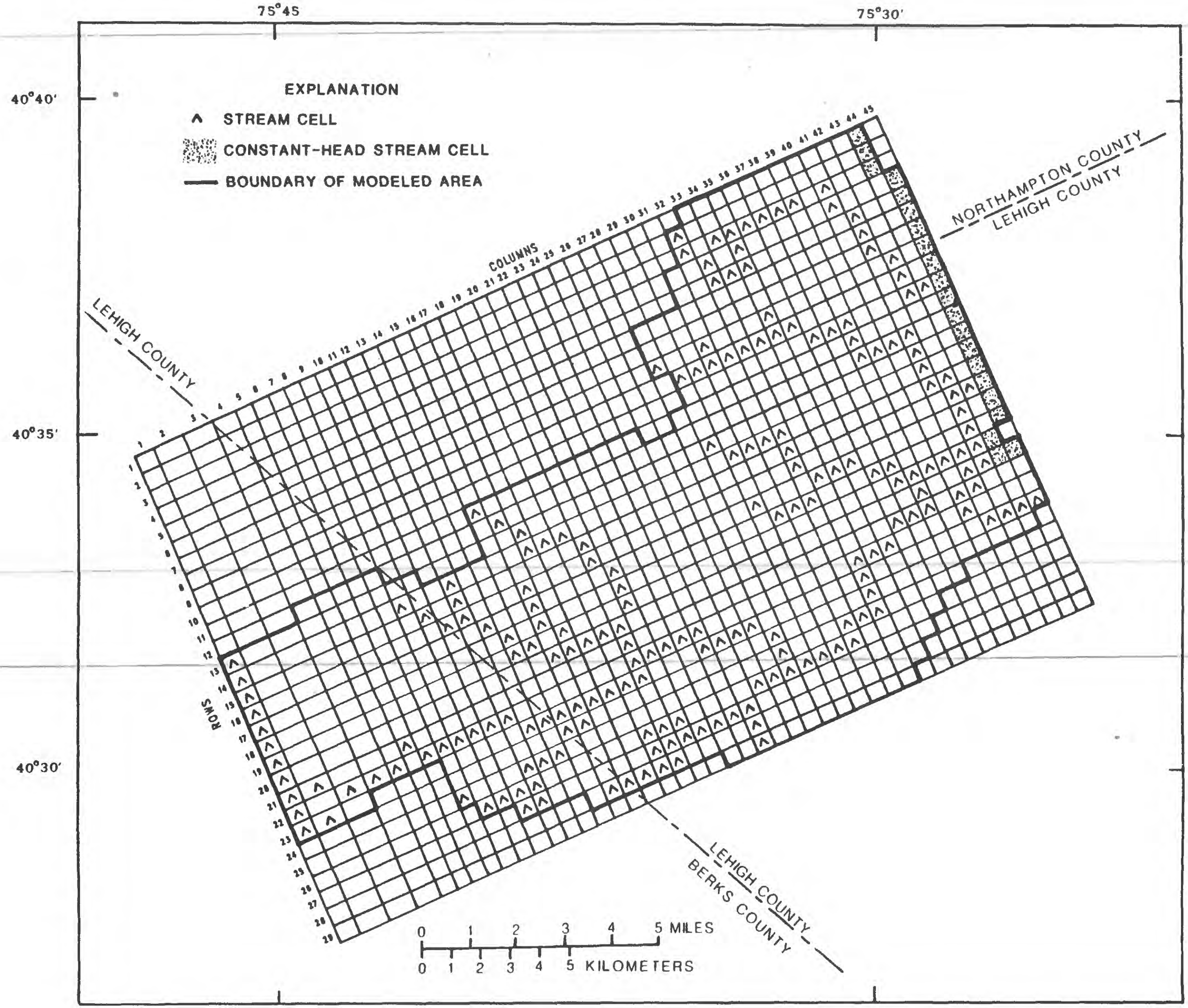


Figure 18.--Location of stream cells.

Aquifer characteristics

Aquifer characteristics required by the model include altitude of the top and bottom of the aquifer, aquifer thickness, aquifer horizontal hydraulic conductivity, aquifer anisotropy, drain (spring) hydraulic conductance[1], drain (spring) elevation, and streambed vertical hydraulic conductance.

The top of the aquifer is the land surface. Average land-surface elevation for each cell was determined from 7.5-minute topographic maps.

Aquifer thickness was assumed to be 600 ft for model simulations on the basis of analysis of water-bearing zones. Few water-bearing zones are penetrated below a depth of 600 ft (table 3), and ground-water circulation below a depth of 600 ft is considered negligible. The altitude of the bottom of the aquifer for each cell was set at 600 ft below the average land-surface elevation for that cell.

Each geologic unit was assigned a different hydraulic conductivity. If a cell contained two geologic units of nearly equal area, the mean hydraulic conductivity of the two units was used; otherwise, the hydraulic conductivity of the predominant unit was assigned to the cell.

Initial aquifer hydraulic conductivity was estimated from specific-capacity data. Transmissivity was estimated from specific capacity using Theis's method for a water-table aquifer (Theis, 1963, p. 332-336):

$$T' = 0.134\ (Q/s)(k - 264 \log_{10} 5\ Sy + 264 \log_{10} t), \qquad (13)$$

and

$$k = -66 - 264 \log_{10} (3.74\ r^2 \times 10^{-6}), \qquad (14)$$

where
T' = estimated transmissivity (ft^2/d),
Q = pumping rate (gal/min),
s = drawdown (ft),
Sy = specific yield,
t = duration of pumping (d),
k = a constant, and
r = well radius (ft).

Because the wells used for analysis have small diameters and tap consolidated rock, r was set equal to well radius (Theis, 1963, p. 335). A specific yield of 0.05, the average used to calculate change in ground-water storage in the water budgets (table 10), was assumed. Hydraulic conductivity was calculated by dividing transmissivity by the depth of uncased borehole (table 13).

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[1] Hydraulic conductance of a block of aquifer material is equal to the hydraulic conductivity of the aquifer material times the cross-sectional area of the block perpendicular to flow divided by the length of the block.

Table 13 illustrates the variability in the hydraulic properties of carbonate rock. For example, estimates of hydraulic conductivity for the Beekmantown Group range over seven orders of magnitude. The mean and median for most units differs by an order of magnitude. Preliminary model simulations using the mean and median hydraulic conductivities gave unsatisfactory results. However, a hydraulic conductivity halfway between the mean and median gave very good results. Therefore, the average of the mean and median hydraulic conductivity was used as the initial hydraulic conductivity for model calibration (table 13). The only adjustment made to hydraulic conductivity during model calibration was to raise the hydraulic conductivity of the Allentown Dolomite from 43 to 47 ft/d and the Beekmantown Group from 78 to 83 ft/d to help calibrate base flow and underflow. The hydraulic conductivity of individual cells was not adjusted. Final calibrated hydraulic conductivities are given in table 13.

Table 13.--Aquifer hydraulic conductivity used for steady-state simulations

[Hydraulic conductivity is based on transmissivity calculated from specific-capacity data by the method of Theis (1963, p. 332). Final estimates of hydraulic conductivity were used in the model.]

		Hydraulic conductivity (feet per day)				
Geologic unit	n	Range	Mean	Median	Initial	Final
Martinsburg Formation	39	0.003- 17.2	1.7	0.8	1.3	1.3
Jacksonburg cement rock facies	19	.01 - 194	15.8	3.8	9.8	9.8
Jacksonburg limestone facies	16	.009- 21.2	3.9	2.3	3.1	3.1
Beekmantown Group	51	.009-1,480	123	33	78	83
Allentown Dolomite	60	.02 -1,200	76	9.9	43	47
Leithsville Formation	14	1.7 - 903	236	14.3	125	125
Hardyston Quartzite	10	.004- 141	10.3	3.4	6.9	6.9

Ground-water flow in the noncarbonate rocks is local; most ground water is discharged to nearby streams draining the noncarbonate rocks. Some ground water flows from the noncarbonate rocks to adjacent carbonate rocks. On the basis of local ground-water divides in the noncarbonate rocks adjacent to the carbonate rocks, ground water flows from 4.2 mi^2 of the Hardyston Quartzite and 0.9 mi^2 of the Martinsburg Formation to carbonate rocks of the Little Lehigh Creek basin above streamflow-gaging station 01451500. The average annual quantity of ground water flowing from the noncarbonate to the carbonate rocks is estimated as 2.58×10^8 ft^3 by calculating the quantity of recharge (21.75 in/yr) on 5.1 mi^2 of noncarbonate rocks draining to carbonate rocks. This quantity of water is equal to 1.89 in/yr (7.27 Mgal/d) entering the carbonate rocks above streamflow-gaging station 01451500.

Hydraulic conductance for each head-dependant boundary node at the contact between the carbonate and noncarbonate rocks was calculated using equation 10. Hydraulic conductivities were based on table 13. The flow length was set equal to the distance to the nearest local ground-water divide in the noncarbonate rocks. Initial estimates of hydraulic conductance produced too much inflow to the carbonate rocks and were reduced. Hydraulic conductance assigned to nodes along the northwestern model boundary (head-dependent boundary) at the contact between the carbonate rocks and the Martinsburg Formation ranged from 41 to 514 ft^2/d. Hydraulic conductance assigned to nodes along the southeastern model boundary (head-dependent boundary) at the contact between the carbonate rocks and the Hardyston Quartzite ranged from 34 to 1,802 ft^2/d. Simulated inflow to the carbonate rocks using these hydraulic conductances is 2.02 in/yr.

Schantz and Crystal Springs are simulated as drains using equation 12. These spring systems are complex and not well understood. They are poorly simulated as drains, although the drain package of the McDonald and Harbaugh (1988) model program is the most suitable method for simulating springs. Simulations using the actual drain elevations produced discharges less than the 1975-83 average discharges. In order to simulate the hydrologic system, a volume of water equal to the 1975-83 average spring discharge had to discharge from the aquifer at the spring cells. Therefore, drain conductance and drain elevation were adjusted to simulate 1975-83 average spring discharges of 7.4 Mgal/d for Schantz Spring and 4.0 Mgal/d for Crystal Spring. Drain conductances of 80,000 ft/d and 71,000 ft/d were assigned to Schantz and Crystal Springs, respectively. Spring elevations were set to 312 ft for Schantz Spring and 250 ft for Crystal Spring.

The water-table aquifer system is considered to be horizontally isotropic. Analysis of aquifer-test data from wells LE-1319 and LE-1355 did not show a preferential direction of transmissivity. The model grid is oriented parallel to strike. A column-to-row anisotropy multiplication factor of 1.0 was used, so that hydraulic conductivity along strike was equal to hydraulic conductivity across strike.

The ground-water and surface-water systems in the Little Lehigh Creek basin are well connected, and water moves freely between the two systems. The direction and rate of water movement between the two systems is controlled by the vertical hydraulic conductivity of the streambed material, thickness of streambed material, and the difference between head in the aquifer and stream stage. Streambed material differs greatly from place to place and consists of gravel, sand, and(or) clay. The vertical hydraulic conductivity of the streambed materials is highly variable and is not known. Therefore, a streambed hydraulic conductance of 10,000 ft/d was assigned to all stream cells. Streambed thickness was assumed to be 1 ft.

Pumping rates

Average 1975-83 pumpage from the modeled area is 7.55 Mgal/d. Pumpage from the Little Lehigh Creek basin above streamflow-gaging station 01451500 is 5.04 Mgal/d, which is 67 percent of the pumpage in the modeled area. Pumpage includes all municipal and private water purveyors and major industrial users of ground water. Pumpage from domestic and commercial wells is not included. Figure 19 shows the annual ground-water pumpage from the Little Lehigh Creek basin above streamflow-gaging station 01451500 and the modeled area for 1975-83. Ground-water pumpage data prior to 1975 generally are not available. Ground-water pumpage increased only slightly from 1976-82. Pumping rates (table 14) used in model simulations are 1975-83 average rates.

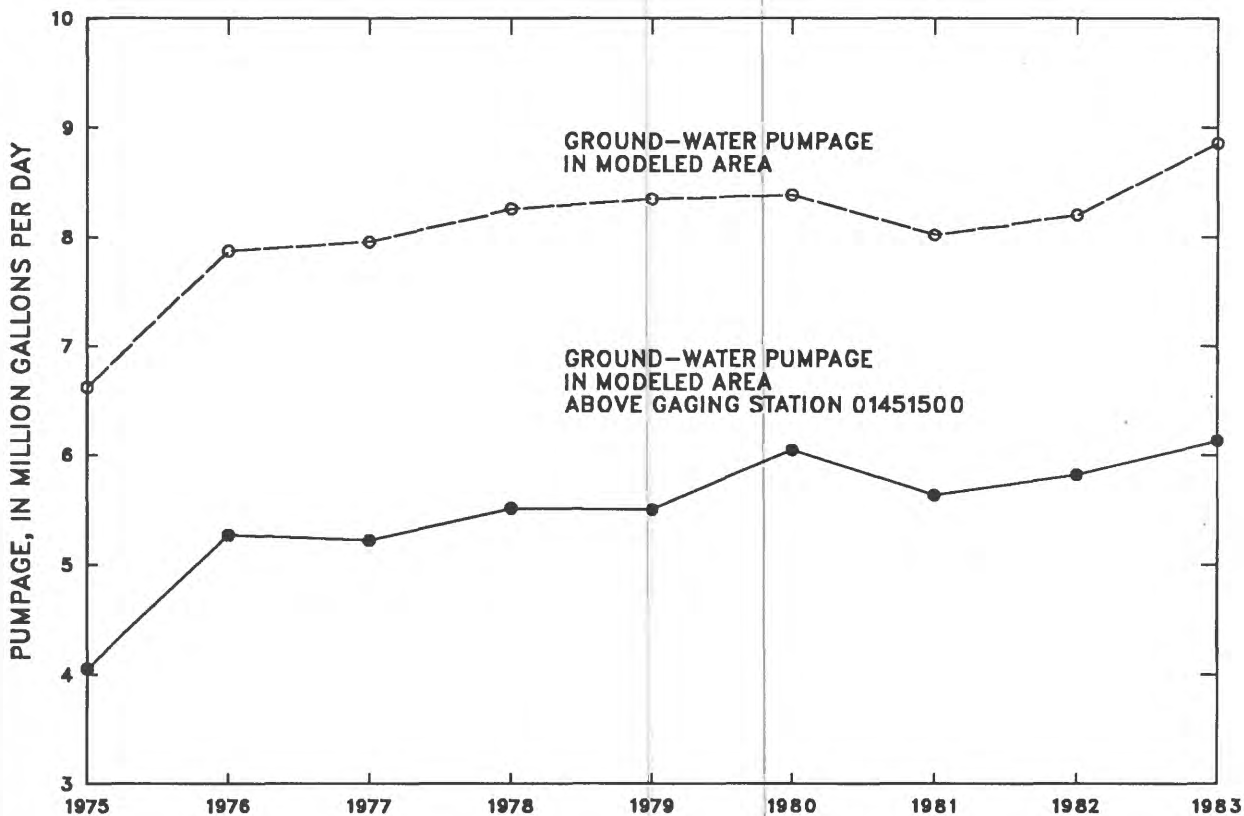


Figure 19.--Annual ground-water pumpage, 1975-83.

Table 14.--Pumping rates used for model simulations
[Mgal/yr, million gallons per year]

Node Row	Node Column	Pumping rate (Mgal/yr)	Well identification number	Owner
8	30	0.339	LE-1312	South Whitehall Township
8	32	.339	LE-1000	South Whitehall Township
8	41	4.695	LE-500	Whitehall Township
9	36	1.780	LE-263, 265, 268, 1107, 1108, 1109	IML Industries
10	30	474.0	LE-1337	Alpo Pet Food
11	41	7.270	LE-593	Whitehall Township
11	42	17.832	LE-499	Whitehall Township
12	18	272.442	LE-1291	Lehigh County Authority
12	27	13.654	LE-533	Greenhill Water Company
12	32	10.502	LE-1348, 1359	Country Club Gardens Water Company
12	33	10.502	LE-1346, 1347	Country Club Gardens Water Company
13	20	224.590	LE-1289	Lehigh County Authority
13	24	90.861	LE-1292	Lehigh County Authority
14	36	10.245	LE-71, 72, 532	Grandview Water Company
16	21	269.916	LE-1290	Lehigh County Authority
16	31	46.538	LE-207, 705	South Whitehall Township
16	32	30.638	LE-525	South Whitehall Township
16	42	105.0	LE-226	SMS Textile
17	13	5.475	LE-1343, 1344, 1345	Terry Hill Mobile Home Park
17	31	24.108	LE-524	South Whitehall Township
18	22	8.1	LE-678	Packaging Corporation of America
18	30	84.680	LE-810, 1349	Cedarbrook Nursing Home
18	32	1.2	LE-1320	Huntsicker
19	25	12.045	LE-597, 800, 801	Red Maples Trailer Court
19	29	1.020	LE-714, 804	Eastern Industries
19	34	5.504	LE-529, 530	Country Club Gardens Water Company
20	22	53.365	LE-506	Lehigh County Authority
20	26	29.064	LE-505	Lehigh County Authority
20	30	14.610	LE-502, 1322	Lehigh County Authority, Country Club Gardens Water Company
20	31	3.053	LE-937, 938, 989	Lehigh County Authority
20	32	15.380	LE-528	South Whitehall Township
20	33	18.295	LE-527	South Whitehall Township
20	34	2.752	LE-531	Country Club Gardens Water Company
21	6	49.378	BE-1049, 1050	Caloric
21	21	29.552	LE-507	Lehigh County Authority
21	27	20.972	LE-710	Lehigh County Authority
21	31	4.278	LE-504	Country Home Acres Water Company
22	5	15.452	BE-617, 619	Topton Borough
23	21	20.789	LE-1295, 1300	Lehigh County Authority
24	29	38.047	LE-1293	Lehigh County Authority
25	26	23.299	LE-1294	Lehigh County Authority
25	33	12.0	LE-410, 677	Lehigh Country Club
26	22	3.05	LE-1332	Mack Truck
26	23	3.05	LE-1285	Mack Truck
26	24	8.566	LE-1321	Lehigh County Authority
26	26	12.0	LE-463, 588	Brookside Country Club
26	32	84.985	LE-1318	Emmaus Borough
26	36	57.463	LE-87	Emmaus Borough
27	19	27.5	LE-1341	Alburtis Borough
27	33	44.720	LE-479	Emmaus Borough
28	24	54.850	LE-193, 891	Macungie Borough, Allen Organ
28	25	23.284	LE-544	Macungie Borough
28	35	191.082	LE-84, 85	Emmaus Borough
29	31	133.376	LE-521	Emmaus Borough
29	32	29.055	LE-86	Emmaus Borough

Simulated water-table surface

The 1975-83 average simulated water-table surface in the Little Lehigh Creek basin (fig. 20) was compared to the observed water-table surface for 1984 (fig. 9). The observed water-table surface was mapped using 20-ft contours. Simulated heads in the carbonate rocks of the Little Lehigh Creek basin were compared with observed heads using the root mean square error (RMSE) difference between observed and simulated heads. The RMSE is the square root of the sum of the squared difference between the observed and simulated head divided by the number of heads and was calculated using the following equation:

$$RMSE = \sqrt{\frac{\Sigma (h_o - h_p)^2}{n}} \qquad (15)$$

where h_o = observed head,

h_p = simulated head, and

n = number of cells.

For steady-state calibration, an RMSE of 21.19 ft was obtained for 316 cells in the Little Lehigh Creek basin. The average difference between simulated and observed head (absolute values) is 14 ft. Simulated heads generally are a little higher than observed heads.

The model-simulated water-table surface (fig. 20) reproduces the observed water-table surface poorly because (1) the simulated head is the average head simulated over a 0.25-mi^2 block of the aquifer rather than the head at a discrete point; and (2) a density of four simulated water-table-surface altitude points per square mile, with the water-table surface elevation at the center of each node, provides insufficient resolution.

Simulated average water budget

The average (1975-83) water budget for the Little Lehigh Creek basin was approximated by a steady-state simulation. The simulated water budget is compared to the calculated water budget in table 15. The calculated base flow in table 15 is the 1975-83 average base flow (table 12). The model simulates base flow only from the carbonate rocks; however, base flow measured at gaging station 01451500 on Little Lehigh Creek includes base flow from both the carbonate and noncarbonate rocks. Base flow contributed by noncarbonate rocks in the basin was measured during July 1989. Fourteen streams were measured at the boundary of the modeled area. Total base flow contributed to the modeled area by the noncarbonate rocks was 20.2 ft^3/s; the flow of Little Lehigh Creek at gaging station 01451500 was 102.5 ft^3/s. Therefore, noncarbonate rocks contributed 20 percent of the base flow measured at the gaging station. The flow at the gaging station was 17 percent higher than the 1975-83 average base flow (87.6 ft^3/s). Base-flow contribution from the noncarbonate rocks is assumed to be 20 percent of base flow measured at the gaging station. The 1975-83 average base flow from the carbonate rocks was, therefore, estimated to be 20 percent of 14.78 in. (87.6 ft^3/s) or 11.82 in. (70.1 ft^3/s); the estimated contribution from the noncarbonate rocks is 2.96 in. (17.5 ft^3/s). The simulated base flow from the carbonate rocks is 11.85 in. (70.2 ft^3/s). Simulated base flow from the carbonate rocks (70.2 ft^3/s) plus estimated base flow from the noncarbonate rocks (17.5 ft^3/s) is equal to the 87.7 ft^3/s simulated base flow from the Little Lehigh Creek basin above gaging station 01451500 in table 15.

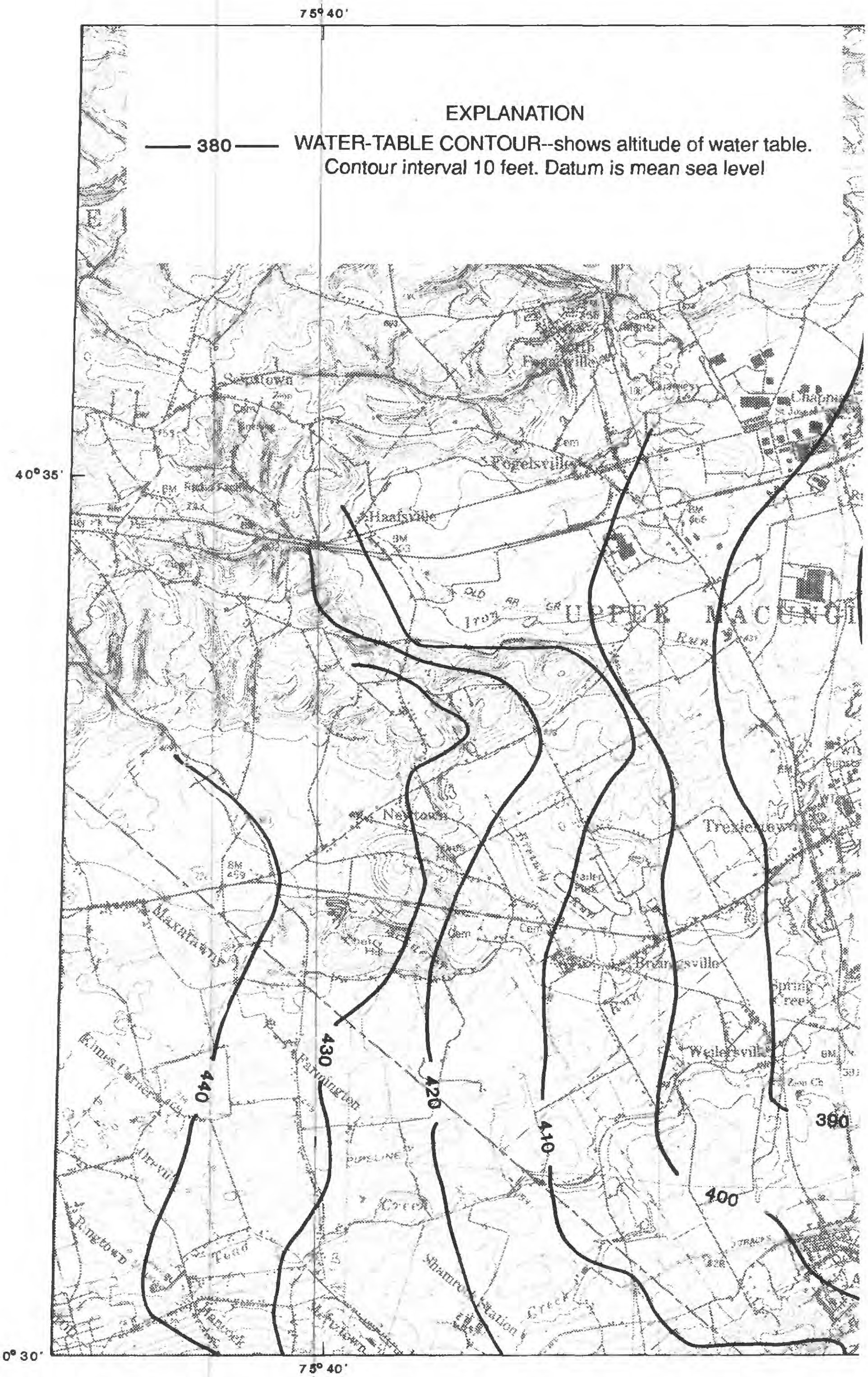
Table 15 lists the simulated net ground-water underflow beneath the surface-water divide on the eastern side of the Little Lehigh Creek basin. Simulated underflow is 4.04 in. (15.54 Mgal/d) out of the basin, which is nearly equal to the estimated underflow of 4.00 in. (15.39 Mgal/d). The model also simulates 0.1 in/yr (0.38 Mgal/d) of inflow from the Sacony Creek basin to the west.

Simulated ground-water ET (0.63 in/yr) is less than estimated ground-water ET (1.5 in/yr). The quantity of simulated ground-water ET can be increased by raising the maximum ET rate or lowering the ET extinction depth; however, the values used for these variables to produce 1.5 in/yr of ET would be unreasonable.

Table 15.--Simulated average water budget for the Little Lehigh Creek basin and simulated spring discharge

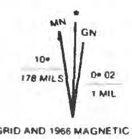
[in/yr, inches per year; ft^3/s, cubic feet per second; Mgal/d, million gallons per day]

	Calculated	Simulated
Water budget		
Recharge	21.75 in/yr	21.75 in/yr
Base flow	87.6 ft^3/s (14.78 in/yr)	87.7 ft^3/s (14.80 in/yr)
Ground-water evapotranspiration	1.50 in/yr	.63 in/yr
Ground-water withdrawals	5.04 Mgal/d (1.31 in/yr)	5.04 Mgal/d (1.31 in/yr)
Underflow out of basin to west	15.39 Mgal/d (4.00 in/yr)	15.54 Mgal/d (4.04 in/yr)
Underflow into basin from west	0.0 Mgal/d (0.0 in/yr)	.38 Mgal/d (.10 in/yr)
Inflow from noncarbonate rocks	7.27 Mgal/d (1.89 in/yr)	7.77 Mgal/d (2.02 in/yr)
Spring discharge		
Schantz Spring discharge	7.4 Mgal/d	7.4 Mgal/d
Crystal Spring discharge	4.0 Mgal/d	4.0 Mgal/d



Base from U.S. Geological Survey

Berks County 1:50,000, 1978
Lehigh County 1:50,000, 1988



UTM GRID AND 1966 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

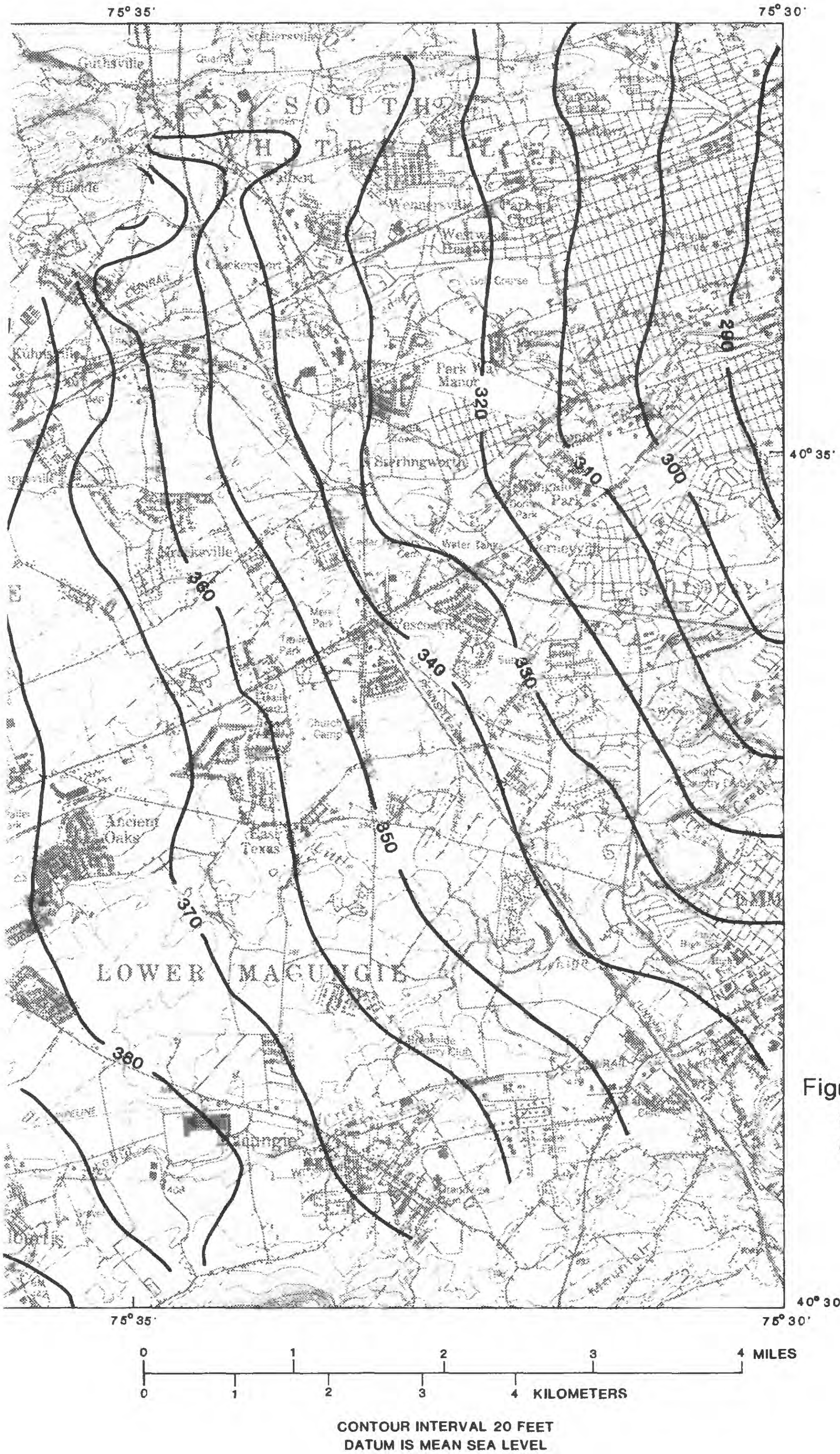


Figure 20.--Simulated water-table surface in the Little Lehigh Creek basin.

Sensitivity analysis

A sensitivity analysis of model variables involves varying the value of a single model variable while holding the others constant. The effect of varying the value of a particular model variable on the simulated water budget and head was determined by varying the value of the variable being tested over a reasonable range, while the values of the other variables remained fixed. Then, any changes in the simulated water budget or head are caused only by the change in the value of the variable being tested. If the changes in the value of a variable causes a relatively large change in the simulated water budget or head, the model is said to be sensitive to that variable. Conversely, if changes in the simulated water budget or head are relatively slight, the model is considered to be insensitive to that variable. In this report, the model is considered as being very sensitive, moderately sensitive, and insensitive to changes in the value of model variables; degree of sensitivity is relative.

The variables tested for sensitivity are aquifer hydraulic conductivity, aquifer thickness, streambed hydraulic conductance, recharge rate, ground-water evapotranspiration rate, evapotranspiration extinction depth, head-dependent boundary hydraulic conductance, and head in the source supplying water to head-dependent boundary cells. The results of a final sensitivity analysis, made when model calibration was completed, are presented below. The value of model variables was varied over a range from half to double the calibrated value; the head in the source supplying water to head-dependent boundary cells was raised and lowered 50 ft. The effects of changing the value of a model variable on base flow from the carbonate rocks are shown on figures 21 and 22. The effects of changing the value of a model variable on the RMSE between observed and simulated head are shown on figures 23 and 24. On figures 21 and 22, slope is directly proportional to sensitivity. A low slope indicates low sensitivity (or insensitivity); a high slope indicates high sensitivity.

The model was found to be very sensitive to the recharge rate (figs. 21 and 23). When the recharge rate was varied from half to double the 1975-83 average rate (10.88 to 43.50 in/yr), the simulated base flow from the carbonate rocks ranged from 32.8 to 153 ft^3/s (53 percent less to 118 percent greater than the 1975-83 average base flow of 70.2 ft^3/s). The RMSE ranged from 20.44 to 26.12 ft.

The model was moderately sensitive to aquifer hydraulic conductivity, aquifer thickness, streambed hydraulic conductance, and head in the source supplying water to head-dependent boundary cells. When aquifer hydraulic conductivity was varied from half to double the calibrated values, the simulated base flow ranged from 53.8 to 79.7 ft^3/s (23 percent less to 14 percent greater than the 1975-83 average base flow of 70.2 ft^3/s). The RMSE ranged from 19.27 to 24.87 ft. When aquifer thickness was varied from 300 to 1,200 ft, the simulated base flow ranged from 51.1 to 80.4 ft^3/s (27 percent less to 15 percent greater than the 1975-83 average base flow). The RMSE ranged from 19.08 to 25.48 ft. When the streambed hydraulic conductance was varied from half to double the calibrated value (5,000 to 20,000 ft^2/d), the simulated base flow ranged from 61.6 to 79.7 ft^3/s (12 percent less to 14 percent greater than the 1975-83 average base flow). The RMSE ranged from 21.00 to 22.18 ft. When head in the source supplying water to head-dependent boundary cells was raised and lowered 50 ft (figs. 22 and 24), the simulated base flow ranged from 63.7 to 80 ft^3/s (14 percent less to 9 percent greater than the 1975-83 average base flow of 70.2 ft^3/s). The RMSE ranged from 20.70 to 21.41 ft. The inflow from the noncarbonate rocks to the carbonate rocks ranged from 1.77 to 16.12 Mgal/d (77 percent less to 108 percent greater than the estimated 7.77 Mgal/d inflow).

The model was insensitive to the ground-water evapotranspiration rate and evapotranspiration extinction depth over the range tested and the head-dependent boundary hydraulic conductance over most of the range tested (figs. 21 and 23). When the ground-water evapotranspiration rate was varied from half to double the 1975-83 average rate (10.05 to 40.18 in/yr), the simulated base flow ranged from 69.4 to 70.5 ft^3/s (1.2 percent less to 0.3 percent greater than the 1975-83 average base flow of 70.2 ft^3/s). The RMSE ranged from 21.14 to 21.19 ft. Simulated ground-water evapotranspiration ranged from 0.32 to 1.21 in/yr. When the evapotranspiration extinction depth was varied from half to double (5 to 20 ft), the simulated base flow ranged from 69.9 to 70.4 ft^3/s (0.5 percent less to 0.3 percent greater than the 1975-83 average base flow of 70.2 ft^3/s). The RMSE was 21.19 ft for all simulations. Simulated ground-water evapotranspiration ranged from 0.36 to 1.21 in/yr. When the head-dependent boundary hydraulic conductance was varied from half to double the calibrated values, the simulated base flow ranged from 68.9 to 78 ft^3/s (0.6 percent less to 11 percent greater than the 1975-83 average base flow). The RMSE ranged from 20.88 to 21.19 ft. The inflow from the noncarbonate rocks to the carbonate rocks ranged from 4.04 to 14.20 Mgal/d (48 percent less to 83 percent greater than the estimated 7.77 Mgal/d inflow).

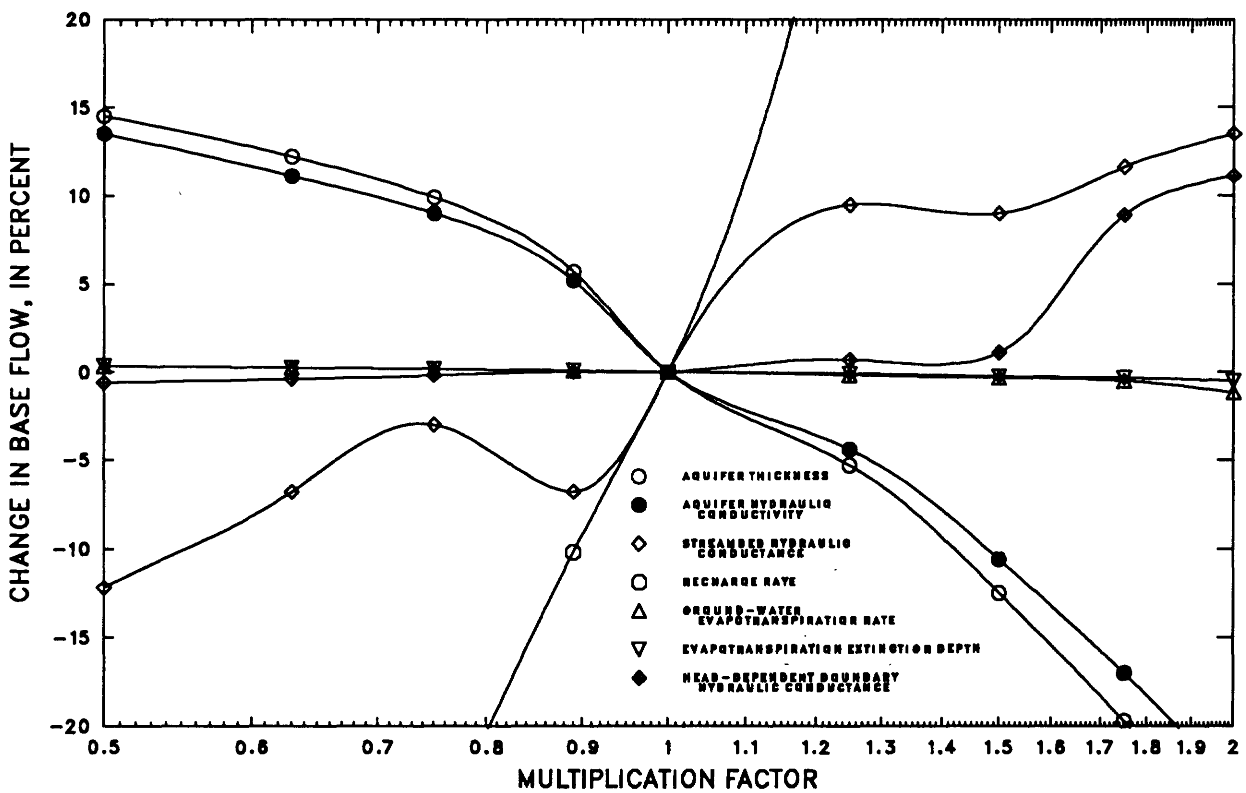


Figure 21.--Effect of varying the value of model variables on base flow.

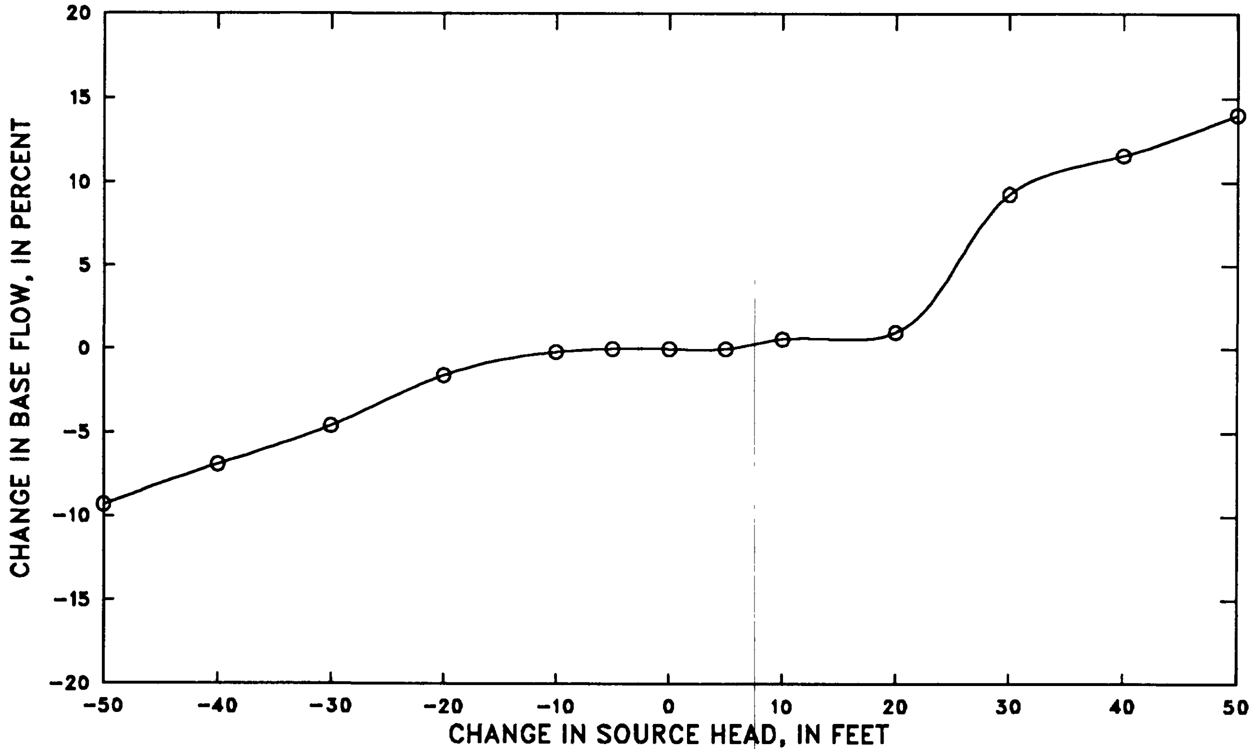


Figure 22.--Effect of varying the head in the source bed supplying water to head-dependent boundary nodes on base flow.

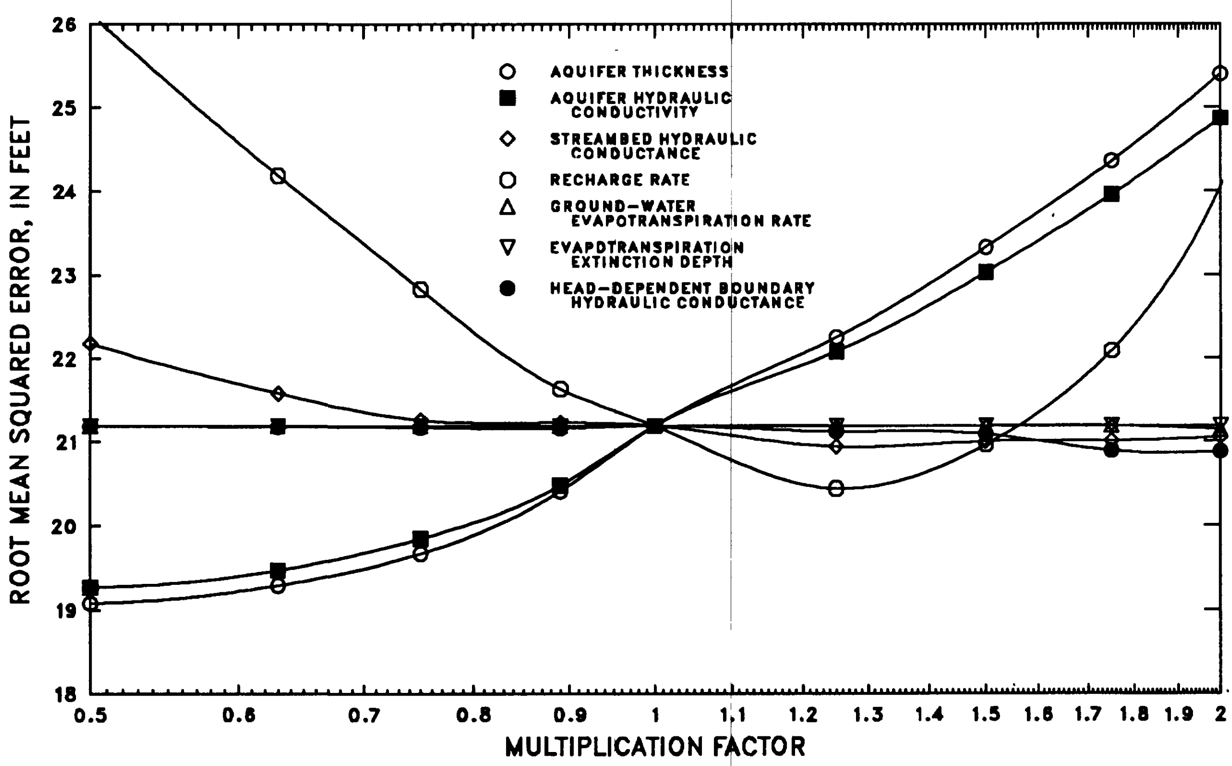


Figure 23.--Effect of varying the value of model variables on the root mean squared error between observed and simulated head.

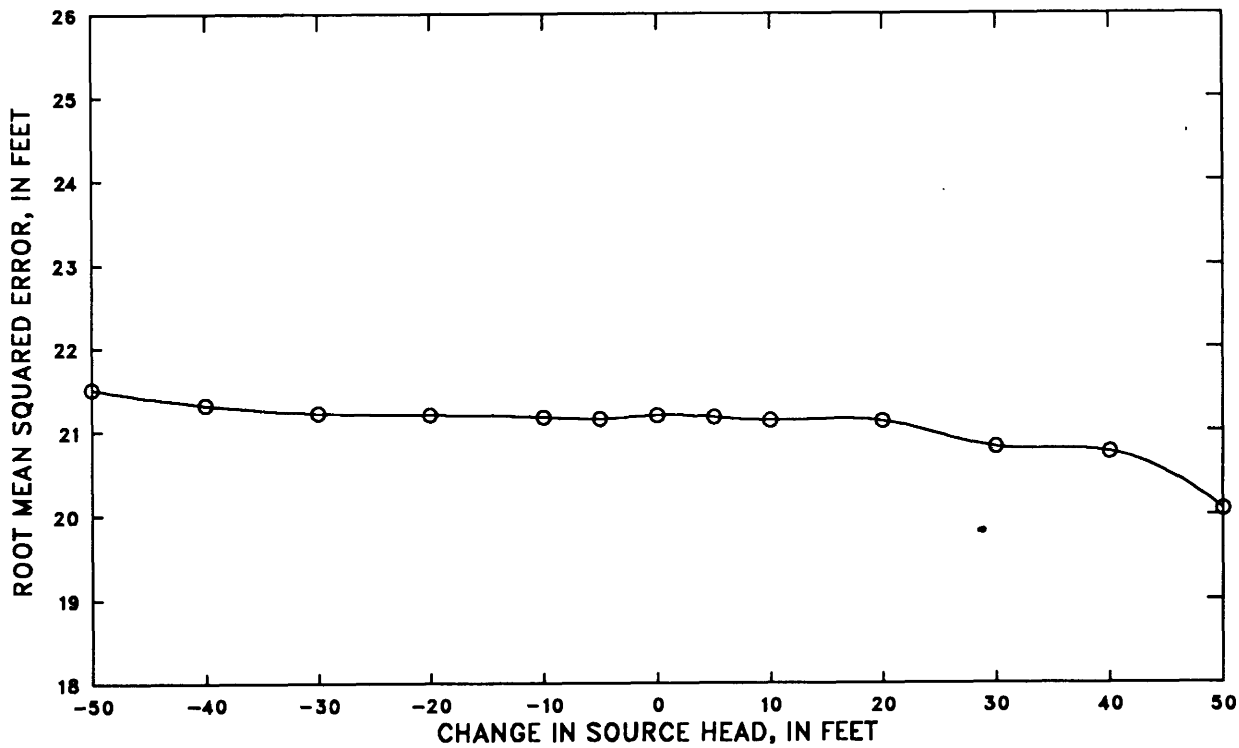


Figure 24.--Effect of varying the head in the source bed supplying water to head-dependent boundary nodes on the root mean squared error between observed and simulated head.

<u>Reliability of model simulations</u>

The ground-water-flow model is a regional model and is considered to be calibrated for the Little Lehigh Creek basin under average conditions. It is useful for simulating the effects of stresses in the basin on the average water budget. It cannot provide estimates of site-specific effects such as head or drawdown at a particular well site or stream infiltration at a particular stream site.

Springs are poorly simulated by the model. Springs are simulated as drains rather than as outlets for a conduit system, which cannot be simulated by the model computer program. Model variables used to simulate springs were set to provide the appropriate spring discharge necessary for model simulations; they do not reflect field values. Therefore, the model cannot be used to assess the effects of stresses on spring flow.

Simulated Effects of Increased Ground-Water Development

The effects of increased ground-water development on base flow and underflow out of the Little Lehigh Creek basin above gaging station 01451500 were simulated for average and drought conditions. Increased ground-water pumping was simulated by locating a hypothetical well field in different parts of the basin. Steady-state simulations were used to represent equilibrium conditions, which would be the maximum expected long-term effect.

Starting heads used for the simulations (fig. 20) were based on results of the final steady-state model calibration. In addition to the hypothetical pumping, average ground-water pumping-rates used for steady-state calibration (table 14) were used for these simulations.

Increased ground-water development in the Little Lehigh Creek basin was simulated as existing wells and hypothetical well fields pumping at the rate of: (1) one-half the 10-percent frequency of 1946-86 average annual base flow, which is equal to 22.8 ft^3/s (3.85 in/yr) or 14.81 Mgal/d (rounded to 15 Mgal/d); (2) 10-percent frequency of 1946-86 average annual base flow, which is equal to 45.6 ft^3/s (7.69 in/yr) or 29.58 Mgal/d (rounded to 30 Mgal/d); and (3) 50-percent frequency of 1946-86 average annual base flow, which is equal to 76.6 ft^3/s (12.97 in/yr) or 49.88 Mgal/d (rounded to 50 Mgal/d). The 1975-83 average pumping rate is 5.01 Mgal/d (rounded to 5 Mgal/d). The frequency distribution of annual average base flow for Little Lehigh Creek near Allentown (gaging station 01451500) for 1946-86 is shown on figure 25, which graphically displays the data in table 4. The 10-percent frequency of 1946-86 average annual base flow is assumed to represent the dry-year base flow. The 50-percent frequency base flow is equal to the median of the 1946-86 annual base flows.

The 1975-83 average base flow simulated by the model is 87.7 ft^3/s (14.80 in.). A ground-water pumping rate of 15, 30, and 50 Mgal/d is equal to 26, 53, and 88 percent of the 1975-83 average base flow, respectively.

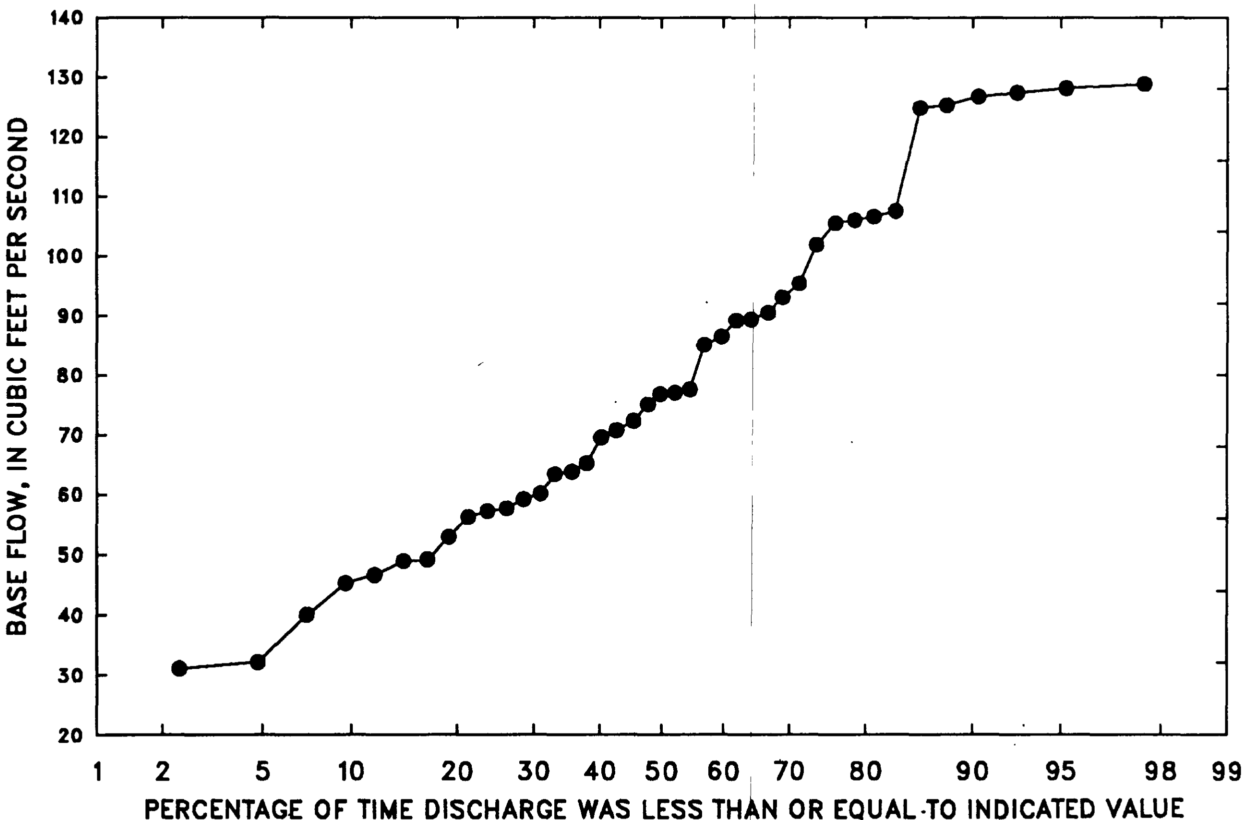


Figure 25.--Frequency distribution of base flow of Little Lehigh Creek near Allentown, 1946-86.

Four hypothetical well fields were located near and away from Little Lehigh Creek in upstream and downstream areas (fig. 26) to estimate the effects of the location of pumped wells relative to the creek. Pumpage from the well fields is equal to the pumpage given above minus the 1975-83 average pumpage (5.04 Mgal/d). Pumpage to simulate increased ground-water development was divided equally among 10 nodes. Therefore, each node in the well field is pumped at 1 Mgal/d for the one-half 10-percent base-flow simulation (total of 10 Mgal/d), 2.5 Mgal/d for the 10-percent base-flow simulation (total of 25 Mgal/d), and 4.5 Mgal/d for the 50-percent base-flow simulation (total of 45 Mgal/d).

The major sources of additional water pumped from wells are diverted base flow, induced infiltration of streamflow, induced underflow from the Sacony Creek basin, and reduction of underflow to the Cedar Creek basin. Other sources of water include reduction in ground-water storage and evapotranspiration and water induced from outside the modeled carbonate rocks by lowered head gradients. Because a steady-state model is used, the model cannot calculate the change in ground-water storage caused by increased pumping. Reduction in base flow in the model simulations represents diversion of ground water to pumping wells that would have otherwise been discharged to Little Lehigh Creek as base flow.

Well field 1 is located near the headwaters of Little Lehigh Creek and away from the stream (fig. 26). Pumping well field 1 at a rate of 10 Mgal/d would decrease base flow by 7.4 ft^3/s (8.4 percent) and induce an additional 2.54 Mgal/d of underflow from the adjacent Sacony Creek basin (table 16). Underflow to the Cedar Creek basin would be reduced by 0.3 Mgal/d. Pumping well field 1 at a rate of 25 Mgal/d would decrease base flow by 19.2 ft^3/s (21.9 percent) and induce an additional 7.28 Mgal/d of underflow from the Sacony Creek basin. Underflow to the Cedar Creek basin would be reduced by 0.69 Mgal/d. Pumping well field 1 at a rate of 45 Mgal/d would decrease base flow by 33.8 ft^3/s (38.5 percent) and induce an additional 13.55 Mgal/d of underflow from the Sacony Creek basin. Underflow to the Cedar Creek basin would be reduced by 1.84 Mgal/d. Pumping at well field 1 would have greatest effect on inducing underflow from the Sacony Creek basin and the least effect on reducing base flow and underflow to the Cedar Creek basin.

Well field 2 is located near the headwaters of Little Lehigh Creek near the stream (fig. 26). Pumping well field 2 at a rate of 10 Mgal/d would decrease base flow by 10.5 ft^3/s (12 percent) and induce an additional 0.97 Mgal/d of underflow from the Sacony Creek basin (table 16). Underflow to the Cedar Creek basin would be reduced by 0.23 Mgal/d. Pumping well field 2 at a rate of 25 Mgal/d would decrease base flow by 23.6 ft^3/s (26.9 percent) and induce an additional 3.12 Mgal/d of underflow from the Sacony Creek basin. Underflow to the Cedar Creek basin would be reduced by 0.61 Mgal/d. Pumping well field 2 at a rate of 45 Mgal/d would decrease base flow by 39.5 ft^3/s (45 percent) and induce an additional 7.82 Mgal/d of underflow from the Sacony Creek basin. Underflow to the Cedar Creek basin would be reduced by 2.3 Mgal/d. Pumping at well field 2 would have less effect on inducing underflow from the Sacony Creek basin and a greater effect on reducing base flow than would pumping at well field 1 because well field 2 is located closer to the Little Lehigh Creek than is well field 1, and more of the pumpage would come from diverted base flow.

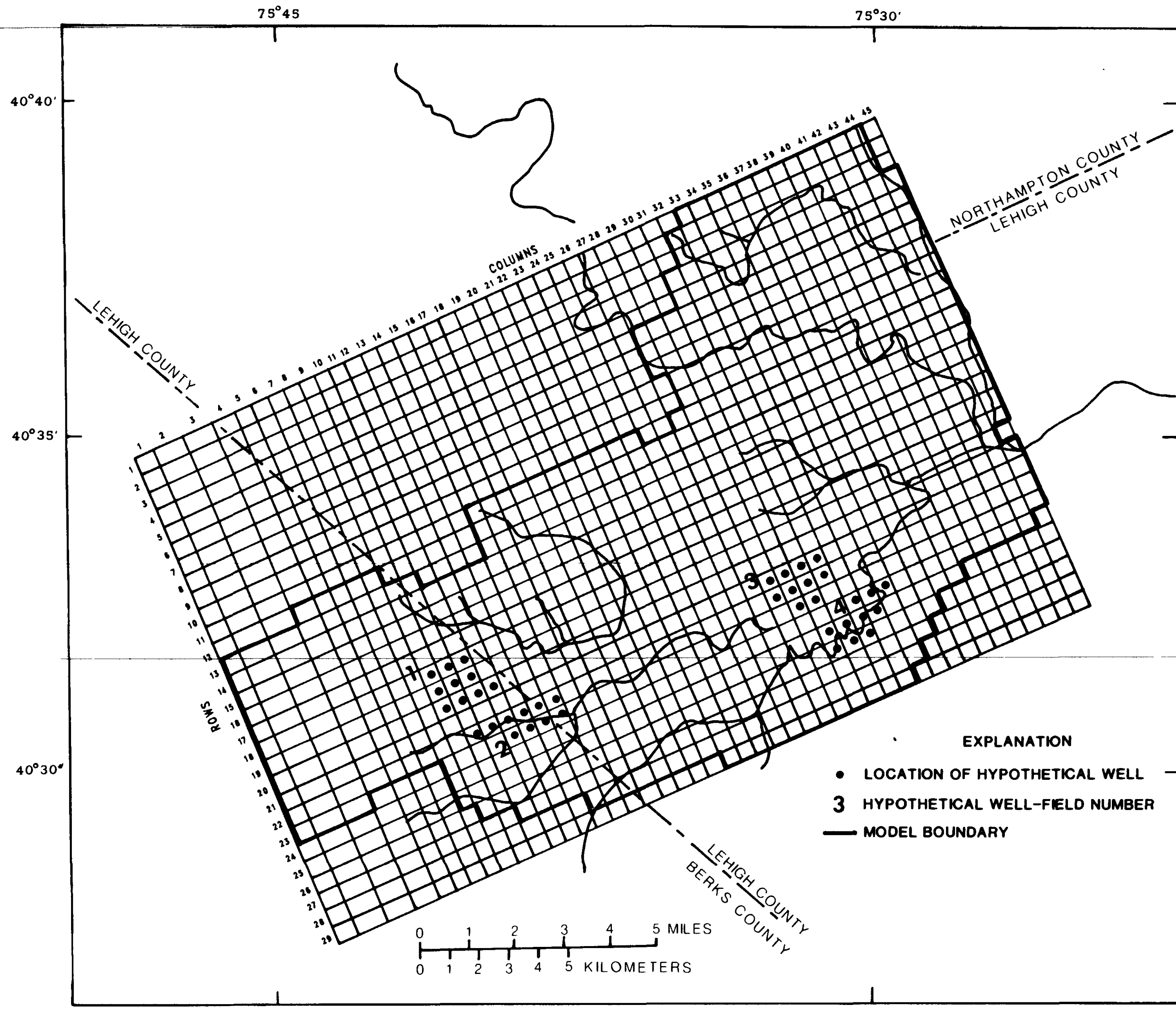


Figure 26.--Locations of hypothetical well fields to simulate increased ground-water development.

Table 16.--Simulated changes in base flow and underflow caused by increased ground-water development for average conditions in the Little Lehigh Creek basin

[Well field locations are shown on figure 26; Mgal/d, million gallons per day; ft^3/s, cubic feet per second]

Well field location	Base flow (ft^3/s)	Change in base flow (percent)	Underflow into (+) or out of (-) the basin from the: East (Mgal/d)	West (Mgal/d)
No additional well field (5 Mgal/d)	87.7	0	-15.54	0.38
Well field 1				
10 Mgal/d	80.3	-8.4	-15.24	2.92
25 Mgal/d	68.5	-21.9	-14.85	7.66
45 Mgal/d	53.9	-38.5	-13.70	13.93
Well field 2				
10 Mgal/d	77.2	-12.0	-15.31	1.35
25 Mgal/d	64.1	-26.9	-14.93	3.50
45 Mgal/d	48.2	-45.0	-13.24	8.20
Well field 3				
10 Mgal/d	79.0	-9.9	-12.58	.23
25 Mgal/d	63.9	-27.1	-8.35	.23
45 Mgal/d	48.1	-45.2	-.96	.31
Well field 4				
10 Mgal/d	77.4	-11.7	-13.70	.19
25 Mgal/d	62.0	-29.3	-10.43	.23
45 Mgal/d	48.2	-45.0	-1.96	.27

Well field 3 is located in the downstream area of the Little Lehigh Creek basin away from the stream (fig. 26). Pumping well field 3 at a rate of 10 Mgal/d would decrease base flow by 8.70 ft^3/s (9.9 percent) and reduce underflow to the Cedar Creek basin by 2.96 Mgal/d (table 16). Pumping well field 3 at a rate of 25 Mgal/d would decrease base flow by 23.8 ft^3/s (27.1 percent) and reduce underflow to the Cedar Creek basin by 7.19 Mgal/d. Pumping well field 3 at a rate of 45 Mgal/d would decrease base flow by 39.6 ft^3/s (45.2 percent) and reduce underflow to the Cedar Creek basin by 14.58 Mgal/d; this would stop nearly all underflow to the Cedar Creek basin under average conditions. Pumping at well field 3 would slightly reduce the underflow from the Sacony Creek basin. Pumping at well field 3 would have the greatest effect on reducing underflow to the Cedar Creek basin because the well field is located closest to the surface-water divide between Little Lehigh and Cedar Creeks.

Well field 4 is located in the downstream area of the Little Lehigh Creek basin near the stream (fig. 26). Pumping well field 4 at a rate of 10 Mgal/d would decrease base flow by 10.3 ft^3/s (11.7 percent) and reduce underflow to the Cedar Creek basin by 1.84 Mgal/d (table 16). Pumping well field 4 at a rate of 25 Mgal/d would decrease base flow by 25.7 ft^3/s (29.3 percent) and reduce underflow to the Cedar Creek basin by 5.11 Mgal/d. Pumping well field 4 at a rate of 45 Mgal/d would decrease base flow by 39.5 ft^3/s (45 percent) and reduce underflow to the Cedar Creek basin by 13.58 Mgal/d. Pumping at well field 4 would slightly reduce the underflow from the Sacony Creek basin. Pumping at well field 4 would have the greatest effect on reducing base flow because the well field is located close to the stream and distant from other sources of water to the pumped wells.

The effects of increased ground-water development on base flow and underflow out of the Little Lehigh Creek basin were simulated for drought conditions. Increased ground-water development was simulated by locating hypothetical well fields in different parts of the basin (fig. 26). The same wells pumped at the same locations and rates that were used for simulations under average conditions also were used for simulations under drought conditions. Steady-state simulations were used to represent equilibrium conditions, which would be the maximum expected effect.

To simulate drought conditions, recharge was reduced from 21.75 in/yr to 12 in/yr. This reduced the base flow of Little Lehigh Creek above streamflow-gaging station 01451500 to 45.5 ft^3/s (7.68 in.), which is comparable to the 1981 water budget (table 12). Base flow includes 36.4 ft^3/s (6.14 in.) from the carbonate rocks and 9.1 ft^3/s (1.54 in.) from the noncarbonate rocks. A ground-water pumping rate of 15, 30, and 50 Mgal/d is equal to 51, 102, and 169 percent of the simulated drought base flow, respectively. Starting heads used for drought-condition simulations are heads simulated when the hydrologic system is in equilibrium with a recharge rate of 12 in/yr.

Pumping well field 1, located near the headwaters of Little Lehigh Creek and away from the stream (fig. 26), under drought conditions at a rate of 10 Mgal/d would decrease base flow by 7.10 ft^3/s (15.6 percent) and induce an additional 3.54 Mgal/d of underflow from the adjacent Sacony Creek basin (table 17). Underflow to the Cedar Creek basin would be reduced by 0.38 Mgal/d. Pumping well field 1 at a rate of 25 Mgal/d would decrease base flow by 16.7 ft^3/s (36.7 percent) and induce an additional 7.62 Mgal/d of underflow from the Sacony Creek basin. Underflow to the Cedar Creek basin would be reduced by 1.62 Mgal/d. Pumping well field 1 at a rate of 45 Mgal/d would decrease base flow by 24.4 ft^3/s (53.6 percent) and induce an additional 8.69 Mgal/d of underflow from the Sacony Creek basin. Underflow to the Cedar Creek basin would be reduced by 8.0 Mgal/d. Pumping at well field 1 would have the greatest effect of any of the pumping scenarios on inducing underflow from the Sacony Creek basin and the least effect on reducing base flow and underflow to the Cedar Creek basin.

Pumping well field 2, located near the headwaters of Little Lehigh Creek near the stream (fig. 26), under drought conditions at the rate of 10 Mgal/d would decrease base flow by 8.6 ft^3/s (18.9 percent) and induce an additional 1.38 Mgal/d of underflow from the Sacony Creek basin (table 17). Underflow to the Cedar Creek basin would be reduced by 0.27 Mgal/d. Pumping well field 2 at the rate of 25 Mgal/d would decrease base flow by 27.2 ft^3/s (40.2 percent) and induce an additional 4.69 Mgal/d of underflow from the Sacony Creek basin. Underflow to the Cedar Creek basin would be reduced by 3.08 Mgal/d. Pumping well field 2 at the rate of 45 Mgal/d would decrease base flow by 25.3 ft^3/s (55.6 percent) and induce an additional 7.69 Mgal/d of underflow from the Sacony Creek basin. Underflow to the Cedar Creek basin would be reduced by 8.85 Mgal/d. Pumping at well field 2 would have less effect on inducing underflow from the Sacony Creek basin and a greater effect on reducing base flow than would pumping at well field 1 because well field 2 is located closer to Little Lehigh Creek than well field 1, and more of the pumpage would come from diverted base flow.

Pumping well field 3, located in the downstream area of the Little Lehigh Creek basin away from the stream (fig. 26), under drought conditions at a rate of 10 Mgal/d would decrease base flow by 9.6 ft^3/s (21.1 percent) and reduce underflow to the Cedar Creek basin by 2.85 Mgal/d (table 17). Pumping well field 3 at the rate of 25 Mgal/d would decrease base flow by 21.9 ft^3/s (48.1 percent) and reduce underflow to the Cedar Creek basin by 8.19 Mgal/d. Pumping well field 3 at a rate of 45 Mgal/d would decrease base flow by 32.3 ft^3/s (80 percent). Underflow would change from an underflow of 15.12 Mgal/d from the Little Lehigh Creek basin to the Cedar Creek basin to an underflow of 2.25 Mgal/d from the Cedar Creek basin to the Little Lehigh Creek basin. Pumping at well field 3 would have the greatest effect of any of the pumping scenarios on the underflow to the Cedar Creek basin.

Table 17.--Simulated changes in base flow and underflow caused by increased ground-water development for drought conditions in the Little Lehigh Creek basin

[Well field locations are shown on figure 26; Mgal/d, million gallons per day; ft^3/s, cubic feet per second]

Well field location	Base flow (ft^3/s)	Change in base flow (percent)	Underflow into (+) or out of (-) the basin from the: East (Mgal/d)	West (Mgal/d)
No additional well field				
(5 Mgal/d)	45.5	0	-15.12	0.81
Well field 1				
10 Mgal/d	38.4	-15.6	-14.74	4.35
25 Mgal/d	28.8	-36.7	-13.50	8.43
45 Mgal/d	21.1	-53.6	-7.12	9.50
Well field 2				
10 Mgal/d	36.9	-18.9	-14.85	2.19
25 Mgal/d	27.2	-40.2	-12.04	5.77
45 Mgal/d	20.2	-55.6	-6.27	8.50
Well field 3				
10 Mgal/d	35.9	-21.1	-12.27	.58
25 Mgal/d	23.6	-48.1	-6.93	.73
45 Mgal/d	13.2	-80.0	2.25	1.12
Well field 4				
10 Mgal/d	34.2	-24.8	-13.39	.54
25 Mgal/d	23.2	-49.0	-8.53	.69
45 Mgal/d	14.6	-67.9	2.58	.88

Pumping well field 4, located in the downstream area of the Little Lehigh Creek basin near the stream (fig. 26), under drought conditions at a rate of 10 Mgal/d would decrease base flow by 11.3 ft^3/s (24.8 percent) and reduce underflow to the Cedar Creek basin by 1.73 Mgal/d (table 17). Pumping well field 4 at a rate of 25 Mgal/d would decrease base flow by 22.3 ft^3/s (49 percent) and reduce underflow to the Cedar Creek basin by 6.63 Mgal/d. Pumping well field 4 at a rate of 45 Mgal/d would decrease base flow by 30.9 ft^3/s (67.9 percent). Underflow would change from an underflow of 15.12 Mgal/d from the Little Lehigh Creek basin to the Cedar Creek basin to an underflow of 2.58 Mgal/d from the Cedar Creek basin to the Little Lehigh Creek basin. Pumping at well field 4 would have the greatest effect on reducing base flow.

The model simulations demonstrate the difficulty of ground-water-resource planning in carbonate-rock terranes. Ground-water-resource planning is often based on a surface-water-basin approach with ground-water withdrawals assumed to cause a one-to-one reduction in base flow. Model simulations show that ground-water withdrawals do not cause a proportional reduction in base flow. Under average conditions, ground-water withdrawals are equal to 48 to 70 percent of simulated base-flow reductions. Under drought conditions, ground-water withdrawals are equal to 35 to 73 percent of simulated base-flow reductions.

The effect of pumping largely depends on the location of the wells. In the Little Lehigh basin, surface-water and ground-water divides do not coincide, and ground-water development, especially near surface-water divides, can cause ground-water divides to shift and induce ground-water underflow from adjacent basins. Large-scale ground-water withdrawals would not necessarily produce reductions of base flow in the basin where pumping takes place because of shifts in the ground-water divide; however, such shifts may reduce base flow in adjacent surface-water basins. For example, the simulated pumping of well field 1 at a rate of 45 Mgal/d under average conditions--a rate equal to 79 percent of the base flow of Little Lehigh Creek--reduces the base flow of Little Lehigh Creek by 38.5 percent; the reduction in base flow is equal to 49 percent of the pumpage. However, 13.55 Mgal/d (30.1 percent of the pumpage) of ground-water that would have been discharged as base flow to Sacony Creek is induced to flow into the Little Lehigh Creek basin by pumping, and the base flow of Sacony Creek is reduced.

SUMMARY

The Little Lehigh Creek basin is underlain mainly by a complex assemblage of highly-deformed Cambrian and Ordovician carbonate rocks. The Leithsville Formation, Allentown Dolomite, Beekmantown Group, and Jacksonburg Limestone act as a single hydrologic unit. Ground water is generally under water-table conditions in the carbonate rocks, but confined conditions exist locally. Ground water moves through fractures and other secondary openings in the carbonate-aquifer system. The yield of wells depends on the size and number of secondary openings intersected below the water table. The frequency of water-bearing zones decreases with depth. Fifty-one percent of water-bearing openings are encountered within 150 ft of land surface, and 82 percent are encountered within 250 ft of land surface.

Aquifer tests were conducted at two wells in the Epler Formation of the Beekmantown Group. Well LE-1319 was pumped for 70 hours at an average rate of 1,900 gal/min. The transmissivity, calculated from results of the aquifer test, was 33,000 ft^2/d. Well LE-1355 was pumped for 74 hours at a rate of 1,400 gal/min. The transmissivity, calculated from results of the aquifer test, was 4,400 ft^2/d.

Ground-water discharge (base flow) comprises 69 to 92 percent of the annual flow of Little Lehigh Creek measured at streamflow-gaging station 01451500 during 1946-86. Annual base flow ranged from 5.24 to 21.74 in/yr. The median ground-water discharge was 12.97 in/yr, which was 82 percent of streamflow.

Ground-water and surface-water divides do not coincide in the Little Lehigh Creek basin. As a result, ground-water underflow to adjoining surface-water basins occurs. The underflow out of the Little Lehigh Creek basin above gaging station 01451500 to the Cedar Creek basin in 1987 is estimated to be about 4 in.

In the western part of the basin, particularly the upper reaches of Iron Run, Schaefer Run, and Toad Creek, streams lose water to the ground-water system when the altitude of the water table at the stream is below the altitude of the stream surface. In the upper part of the Little Lehigh Creek basin, the water table is generally a few feet to tens of feet below stream beds. In the eastern part of the basin, ground water discharges to streams and comprises the base-flow component of streamflow. All streamflow lost in the upper part of the basin returns to Little Lehigh Creek as ground-water discharge to gaining reaches in the lower part of the basin.

Annual water budgets for 1975-83 and an average water budget for those years were prepared for the 80.8 mi^2 part of the basin above gaging station 01451500. For 1975-83, average annual streamflow was 19.09 in., evapotranspiration was 20.09 in., diversions from the basin were 1.30 in., ground-water storage declined 0.16 in., and net underflow out of the basin was estimated to be 4.0 in. Average annual recharge for 1975-83 was 21.75 in.

Cessation of pumping at the Lehigh Portland quarry at Fogelsville and the development of ground water for public supply in the Schantz Spring basin has not affected the flow of Schantz Spring. A double-mass curve of the

cumulative flow of Schantz Spring as a function of cumulative precipitation of Allentown for 1954-84 plots as a straight line, indicating that no change in the constant of proportionality between the flow of Schantz Spring and precipitation occurred.

Ground-water flow in the Little Lehigh Creek basin was simulated by a finite-difference, two-dimensional computer model. The geologic units in the modeled area were simulated as a single water-table aquifer. Recharge to, ground-water flow through, and discharge from the carbonate rocks of the Little Lehigh Creek basin were simulated. Sources of water to the modeled carbonate rocks are areally-distributed recharge from precipitation and lateral ground-water flow from noncarbonate rocks to the north and south of the carbonate valley. Discharge of water from the modeled hydrologic system is by pumping from wells, ground-water discharge to streams, and ground-water evapotranspiration.

The area between the Lehigh River and Sacony Creek was modeled to include the natural hydrologic boundaries of the ground-water-flow system. The modeled area was discretized into a rectangular grid of 29 rows and 45 columns containing 861 active cells representing 134 mi^2. On the northwestern and southeastern sides of the modeled area, the geologic contact between the carbonate and noncarbonate rocks is a head-dependent boundary. On the northeastern side of the modeled area, the Lehigh River is simulated as a specified-head (constant-head) boundary. On the southwestern side, the boundary is Sacony Creek, which is represented by a head-dependent boundary. The model lower boundary is a specified-flux (no-flow) boundary 600 ft below land surface. The model upper boundary is represented by the water-table surface, which is a specified-flux boundary.

The ground-water-flow model of the Little Lehigh Creek basin was calibrated under steady-state conditions using 1975-83 average recharge, evapotranspiration, and pumping rates. The recharge rate used for model simulations was 4.97×10^{-3} ft/d (21.75 in/yr) and the evapotranspiration rate was 4.59×10^{-3} ft/d (20.09 in/yr). Average 1975-83 pumpage from the Little Lehigh Creek basin above gaging station 01451500 is 5.04 Mgal/d.

Each geologic unit was assigned a different hydraulic conductivity. Initial aquifer hydraulic conductivity was estimated from specific-capacity data. Schantz and Crystal Springs were simulated as drains; drain conductance and drain elevation were adjusted to simulate 1975-83 average spring discharges of 7.4 Mgal/d for Schantz Spring and 4.0 Mgal/d for Crystal Spring.

The average (1975-83) water budget for the Little Lehigh Creek basin was approximated by a steady-state simulation. The simulated base flow from the carbonate rocks of the Little Lehigh Creek basin above gaging station 01451500 is 11.85 in/yr. The simulated ground-water underflow from the Little Lehigh Creek basin to the Cedar Creek basin is 4.00 in/yr. For steady-state calibration, the RMSE between observed and simulated heads was 21.19 ft for 316 cells in the Little Lehigh Creek basin.

The model was found to be very sensitive to the recharge rate and moderately sensitive to aquifer hydraulic conductivity, aquifer thickness, streambed hydraulic conductance, and head in the source supplying water to the head-dependent boundary. The model was insensitive to the ground-water evapotranspiration rate, evapotranspiration extinction depth, and head-dependent boundary hydraulic conductance.

The effects of increased ground-water development on base flow and underflow out of the Little Lehigh Creek basin under average and drought conditions were simulated by locating a hypothetical well field in different parts of the basin. Steady-state simulations were used to represent equilibrium conditions, which would be the maximum expected long-term effect.

Increased ground-water development in the Little Lehigh Creek basin was simulated as existing wells and hypothetical well fields pumped at the rate of (1) one-half the 10-percent frequency of 1946-86 average annual base flow (15 Mgal/d), (2) 10-percent frequency of 1946-86 average annual base flow (30 Mgal/d), and (3) 50-percent frequency of 1946-86 average annual base flow (50 Mgal/d). The 1975-83 average pumping rate was 5 Mgal/d. Four hypothetical well fields were located near and away from Little Lehigh Creek in upstream and downstream areas.

Pumping well field 1, located near the headwaters of Little Lehigh Creek and away from the stream, at a rate of 45 Mgal/d under average conditions would decrease the base flow of Little Lehigh Creek by 33.8 ft^3/s (38.5 percent), induce an additional 13.55 Mgal/d of underflow from the Sacony Creek basin, and reduce underflow to the Cedar Creek basin by 1.84 Mgal/d. Pumping well field 1 at a rate of 45 Mgal/d under drought conditions would decrease base flow by 24.4 ft^3/s (53.6 percent), induce an additional 8.69 Mgal/d of underflow from the Sacony Creek basin, and reduce underflow to the Cedar Creek basin by 8.0 Mgal/d. Pumping at well field 1 would have the greatest effect of all the pumping scenarios on inducing underflow from the Sacony Creek basin and the least effect on reducing base flow and underflow to the Cedar Creek basin.

Pumping well field 2, located near the headwaters of Little Lehigh Creek near the stream, at a rate of 45 Mgal/d under average conditions would decrease the base flow of Little Lehigh Creek by 39.5 ft^3/s (45 percent), induce an additional 7.82 Mgal/d of underflow from the Sacony Creek basin, and reduce the underflow to the Cedar Creek basin by 2.3 Mgal/d. Pumping well field 2 at a rate of 45 Mgal/d under drought conditions would decrease base flow by 25.3 ft^3/s (55.6 percent), induce an additional 7.69 Mgal/d of underflow from the Sacony Creek basin, and reduce the underflow to the Cedar Creek basin by 8.85 Mgal/d. Pumping at well field 2 would have less effect on inducing underflow from the Sacony Creek basin and a greater effect on reducing base flow than would pumping at well field 1 because well field 2 is located closer to Little Lehigh Creek than well field 1, and more of the pumpage would come from diverted base flow.

Pumping well field 3, located in the downstream area of the Little Lehigh Creek basin away from the stream, at a rate of 45 Mgal/d under average conditions would decrease the base flow of Little Lehigh Creek by 39.6 ft^3/s

(45.2 percent) and reduce underflow to the Cedar Creek basin by 14.58 Mgal/d; this would stop nearly all underflow to the Cedar Creek basin. Pumping well field 3 at a rate of 45 Mgal/d under drought conditions would decrease base flow by 32.3 ft^3/s (80 percent) and change the underflow of 15.12 Mgal/d from the Little Lehigh Creek basin to the Cedar Creek basin to an underflow of 2.25 Mgal/d from the Cedar Creek basin to the Little Lehigh Creek basin. Pumping at well field 3 would have the most effect of all the pumping scenarios on the underflow to the Cedar Creek basin.

Pumping well field 4, located in the downstream area of the Little Lehigh Creek basin near the stream, at a rate of 45 Mgal/d under average conditions would decrease base flow by 39.5 ft^3/s (45 percent) and reduce underflow to the Cedar Creek basin by 13.58 Mgal/d. Pumping well field 4 at a rate of 45 Mgal/d under drought conditions would decrease base flow by 30.9 ft^3/s (67.9 percent) and change the underflow of 15.12 Mgal/d from the Little Lehigh Creek basin to the Cedar Creek basin to an underflow of 2.58 Mgal/d from the Cedar Creek basin to the Little Lehigh Creek basin. Pumping at well field 4 would have the greatest effect of all the pumping scenarios on reducing base flow.

Model simulations show that ground-water withdrawals do not cause a proportional reduction in base flow. Under average conditions, ground-water withdrawals are equal to 48 to 70 percent of simulated base-flow reductions. Under drought conditions, ground-water withdrawals are equal to 35 to 73 percent of simulated base-flow reductions..

The effect of pumping largely depends on well location. In the Little Lehigh Creek basin, surface-water and ground-water divides do not coincide, and ground-water development, especially near surface-water divides, can cause ground-water divides to shift and induce ground-water underflow from adjacent basins. Large-scale ground-water pumping would not necessarily produce reductions in base flow in the basin where pumping occurs because of shifts in the ground-water divide; however, such shifts could reduce base flow in adjacent surface-water basins.

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Table 18.--Records of selected wells and springs

Local number: BE, well in Berks County; LE, well in Lehigh County; LE-Sp, spring in Lehigh County.

Site-ID: Well location. First six numbers are latitude in degrees, minutes, and seconds. Next seven numbers are longitude in degrees, minutes, and seconds. Last two numbers are sequence number.

Use of site: O, observation well; U, unused; W, withdrawal; Z, destroyed.

Use of water: A, air conditioning; C, commercial; H, domestic; I, irrigation; N, industrial; P, public supply; R, recreational; T, institutional; U, unused; Z, other.

Aquifer codes: 364JKBG, Jacksonburg Limestone, undivided; 364JKBGC, Jacksonburg Limestone, cement limestone facies; 364JKBGR, Jacksonburg Limestone, cement rock facies; 364BKMN, Beekmantown Group; 364ONLN, Onteluantee Formation; 367EPLR, Epler Formation; 371ALNN, Allentown Dolomite, undivided; 371TCKR, Allentown Dolomite, Tuckerton Member; 374LSVL, Leithsville Formation; 377HRDS, Hardyston Quartzite.

Altitude of land surface is estimated from topographic maps. Datum is National Geodetic Vertical Datum of 1929.

Water level is in feet below land surface. A, airline; M, measured; R, reported.

Table 18.--Records of selected wells and springs--Continued

Local number	Site identification number	Owner	Driller	Date drilled	Use of site	Use of water
		BERKS COUNTY				
BE- 617	403000075421401	Topton Borough	--	1935	U	U
619	402954075420701	Topton Borough	--	1921	W	P
623	402615075530501	Maidencreek Township	--	--	U	U
1049	403025075145901	Caloric Corp.	Harry H. Herman	--	W	N
1050	403025075415902	Caloric Corp.	Harry H. Herman	--	W	N
1051	403029075415901	Caloric Corp.	Harry H. Herman	--	W	U
1411	403152075401001	Boyd, Randall	R.H. Odenheiner Co.	1979	W	H
1423	403026075395501	Atlas Minerals & Chemicals, Inc.	R.H. Odenheiner Co.	1964	W	N
1424	403034075400001	Atlas Minerals & Chemicals, Inc.	R.H. Odenheiner Co.	1975	W	N
1445	403055075455802	Kutztown Borough	Harrisburg's Kohl Bros.	1982	W	P
1447	403119075460801	Kutztown Borough	C.S. Garber & Sons, Inc.	1983	W	P
		LEHIGH COUNTY				
LE- 71	403648075312001	Grandview Water Co.	Harry H. Herman	1948	W	P
72	403645075311901	Grandview Water Co.	Harry H. Herman	1951	U	U
84	403222075290301	Emmaus Borough	M.B. Biery	1923	W	P
85	403224075290201	Emmaus Borough	M.B. Biery	1923	W	P
86	403141075301001	Emmaus Borough	Artesian Well Drlg. Co.	1949	W	P
87	403300075285901	Emmaus Borough	C.S. Garber & Sons, Inc.	1951	W	P
193	403052075333601	Allen Organ Co.	--	--	W	U
207	403523075330401	S. Whitehall Twp.	M.B. Biery	1948	W	P
226	403653075285201	S.M.S. Textile Mills	M.B. Biery	1947	W	A
263	403754075322301	IMC Pitman-Moore, Inc.	M.B. Biery	1941	W	N
265	403757075321801	IMC Pitman-Moore, Inc.	M.B. Biery	1944	W	N
268	403755075322101	IMC Pitman-Moore, Inc.	M.B. Biery	--	W	N
410	403255075303901	Lehigh Country Club	M.B. Biery	1927	W	I
463	403130075330502	Brookside Country Club	M.B. Biery	1930	W	I
479	403221075300301	Emmaus Borough	C.S. Garber & Sons, Inc.	1954	W	P
499	403823075293701	Whitehall Twp. Authority	--	1955	W	P
500	403902075301501	Whitehall Twp. Authority	--	--	W	P
502	403409075323601	Country Club Gardens Water Co.	--	1959	W	P
504	403345075314001	Country Home Acres Water Co.	--	1961	W	P
505	403323075340501	Lehigh County Authority	C.S. Garber & Sons, Inc.	1963	W	P
506	403251075353501	Lehigh County Authority	C.S. Garber & Sons, Inc.	1963	W	P
507	403226075354901	Lehigh County Authority	C.S. Garber & Sons, Inc.	1966	W	P
521	403120075303201	Emmaus Borough	R.H. Odenheiner Co.	1961	W	P
524	403512075324001	S. Whitehall Twp. Authority	Harry H. Herman	1952	W	P
525	403519075323101	S. Whitehall Twp. Authority	R.H. Odenheiner Co.	1965	W	P
527	403433075311901	S. Whitehall Twp. Authority	R.H. Odenheiner Co.	1957	W	P
528	403416075315701	S. Whitehall Twp. Authority	R.H. Odenheiner Co.	1960	W	P
529	403447075310101	Country Club Gardens Water Co.	Richard E. Henry	1957	W	P
530	403441075311201	Country Club Gardens Water Co.	R.H. Odenheiner Co.	1957	W	P
531	403437075310601	Country Club Gardens Water Co.	Lehigh Valley Well & Pump Co.	1960	W	P
532	403645075313201	Grandview Water Co.	R.H. Odenheiner Co.	1953	W	P
533	403602075352601	Green Hills Water Co.	R.H. Odenheiner Co.	1964	W	P
544	403105075330201	Macungie Borough	Kermit S. Snyder	1966	W	P
588	403130075330501	Brookside Country Club	R.H. Odenheiner Co.	1962	W	I
593	403818075300301	Whitehall Twp. Authority	R.H. Odenheiner Co.	1961	W	P
597	403817075261502	Witko Trailer Court	R.H. Odenheiner Co.	1961	W	P
644	403429075392401	Haaf, Charles	R.H. Odenheiner Co.	1958	U	U
677	403256075303802	Lehigh Country Club	R.H. Odenheiner Co.	1955	W	R
678	403328075361301	Packaging Corp. of America	R.H. Odenheiner Co.	1955	W	N
705	403523075330301	S. Whitehall Authority	Charles D. Moyer	1967	W	P
710	403323075334801	Lehigh County Authority	C.S. Garber & Sons, Inc.	1964	W	P
714	403413075330501	Eastern Industries, Inc.	Kermit S. Snyder	1960	W	N
800	403341075343101	Red Maple Acres Trailer Court	R.H. Odenheiner Co.	1959	W	P
801	403342075343101	Red Maple Acres Trailer Court	R.H. Odenheiner Co.	1967	W	P
804	403415075330901	Eastern Industries, Inc.	Kermit S. Snyder	1965	W	N
810	403433075324601	Cedarbrook	Harrisburg's Kohl Bros.	1958	W	T
860	403226075343001	Knepper, Paul	C.S. Garber & Sons, Inc.	1967	O	U
866	403438075393801	Lichtenwalner, A.	Claude H. Otter	1963	U	U
891	403051075333701	Allen Organ Co.	C.S. Garber & Sons, Inc.	1961	W	N
937	403416075320401	Clearview Manor Water Co.	Lehigh Valley Well & Pump Co.	1967	W	P
938	403415075320301	Clearview Manor Water Co.	Lehigh Valley Well & Pump Co.	1967	U	U
989	403405075321401	Clearview Manor Water Co.	Lehigh Valley Well & Pump Co.	1968	W	P
1000	403755075340601	S. Whitehall Twp. Authority	Miller Pump Service, Inc.	1968	W	P

Table 18.--Records of selected wells and springs--Continued

Aquifer code	Depth of well (feet)	Depth cased (feet)	Casing diameter (inches)	Elevation of land surface (feet)	Water level (feet)	Date water level measured	Reported yield (gallons per minute)	Reported specific capacity (gal/min)/ft	Local number
					BERKS COUNTY				
374LSVL	297	--	8	500	29.0 R	03-01-1966	192	2.23	BE- 617
374LSVL	248	220	8	520	92.0 M	10-01-1971	367	--	619
374LSVL	385	--	8	430	131 M	08-01-1971	400	13.3	623
371TCKR	400	--	--	470	--	--	--	--	1049
371TCKR	400	--	6	470	--	--	--	--	1050
371TCKR	500	--	6	470	--	--	--	--	1051
371ALNN	175	120	6	490	59.5 R	06-18-1984	20	--	1411
374LSVL	300	94	8	450	45 R	01-28-1964	200	3.6	1423
374LSVL	77	70	6	1,425	40 R	12-05-1975	19	19	1424
367EPLR	506	--	12	405	7 R	07-01-1982	300	4.1	1445
364ONLN	557	--	--	420	--	--	300	1.1	1447
					LEHIGH COUNTY				
371ALNN	490	90	6	420	90.0 R	03-01-1964	50	--	LE- 71
371ALNN	265	90	6	415	--	--	50	--	72
374LSVL	311	--	10	425	64.5 M	05-01-1952	450	--	84
374LSVL	375	--	10	425	56.0 A	05-01-1952	750	--	85
374LSVL	525	166	10	410	44.0 M	05-01-1952	325	2.60	86
374LSVL	187	124	10	465	55.0 R	06-01-1951	350	175	87
374LSVL	800	--	6	380	--	--	--	--	193
364BKMN	276	100	6	430	--	--	--	--	207
371ALNN	1,140	--	--	330	--	--	--	--	226
364BKMN	155	134	12	310	30.0 M	1941	390	32.5	263
364BKMN	145	126	12	310	20.0 M	04-01-1948	465	23.2	265
364BKMN	145	--	--	310	--	--	210	--	268
374LSVL	145	--	12	315	16.0 M	12-01-1954	--	--	410
371ALNN	400	--	8	360	--	--	--	--	463
371ALNN	462	72	10	460	125 A	1955	600	26.1	479
371ALNN	200	79	6	385	--	--	65	32.5	499
371ALNN	185	40	6	365	--	--	60	12.0	500
371ALNN	237	44	8	390	75.0 R	1959	85	--	502
371ALNN	300	70	8	420	87.0 R	05-01-1961	140	8.24	504
371ALNN	305	14	12	470	140 R	05-01-1963	466	93.2	505
371ALNN	206	24	--	415	45.0 R	03-01-1963	348	11.6	506
371ALNN	185	61	8	410	60.0	09-01-1966	400	6.67	507
377HRDS	350	106	12	450	45.0 R	05-09-1961	530	18.0	521
371ALNN	394	60	8	435	65.0 R	06-01-1952	225	22.5	524
371ALNN	428	66	10	410	48.0 R	04-01-1956	550	34.4	525
371ALNN	352	39	8	370	66.0 R	04-01-1957	200	1.92	527
371ALNN	677	52	8	445	121 R	07-01-1960	150	1.26	528
371ALNN	185	40	8	360	65.0 M	08-01-1967	60	3.00	529
371ALNN	175	90	6	360	65.0 R	05-01-1957	65	3.82	530
371ALNN	275	140	6	370	--	--	75	--	531
371ALNN	265	42	6	410	95.0 R	12-01-1953	75	--	532
364JKBG	323	80	8	560	23.0 R	06-01-1964	175	1.33	533
374LSVL	310	102	8	375	27.0 M	02-01-1967	440	18.3	544
371ALNN	109	44	10	360	16.0 R	09-01-1962	600	46.1	588
371ALNN	475	64	10	415	134	10-01-1961	50	--	593
364BKMN	120	26	6	365	50.0 R	10-01-1961	10	--	597
364BKMN	184	63	10	470	75.0 R	07-01-1958	500	125	644
374LSVL	125	47	10	315	16.0 R	08-01-1955	200	--	677
364BKMN	170	96	8	405	--	--	500	--	678
364BKMN	342	91	8	430	81.0 R	02-01-1967	140	--	705
371ALNN	334	184	10	490	142 R	04-01-1964	--	--	710
371ALNN	140	41	10	390	40.0 R	06-01-1960	45	3.00	714
371ALNN	210	143	6	445	69.0 R	09-01-1959	50	--	800
371ALNN	300	60	6	445	100 R	04-01-1967	40	--	801
371ALNN	325	28	8	375	65.0 R	06-01-1965	115	2.09	804
371ALNN	250	111	12	365	--	--	200	--	810
371ALNN	100	58	6	360	6.00 M	07-01-1967	74	--	860
364BKMN	117	82	6	480	78.0 M	07-01-1967	--	--	866
374LSVL	624	93	12	385	19.0 R	08-01-1961	322	--	891
371ALNN	286	167	6	437	117 R	06-01-1967	30	.36	937
371ALNN	256	96	6	437	100 R	08-01-1967	18	.86	938
371ALNN	352	44	6	442	118 M	04-01-1968	17	.14	989
364BKMN	260	84	6	392	86.0 R	02-01-1968	--	--	1000

Table 18.--Records of selected wells and springs--Continued

Local number	Site identification number	Owner	Driller	Date drilled	Use of site	Use of water
		LEHIGH COUNTY--Continued				
LE-1107	403755075322701	IMC Pitman-Moore, Inc.	C.S. Garber & Sons, Inc.	1955	W	N
1108	403757075321301	IMC Pitman-Moore, Inc.	C.S. Garber & Sons, Inc.	1955	W	N
1109	403801075320601	IMC Pitman-Moore, Inc.	C.S. Garber & Sons, Inc.	1955	W	N
1274	403647075271501	Allentown Boat and Swimming Club	--	1909	W	H
1275	403708075281601	Jordan Silk Dyeing Co.	--	1914	W	N
1284	403305075375801	Siravo, Anthony	--	1981	W	H
1285	403105075341501	Mack Trucks, Inc.	William Stothoff Co.	1975	W	H
1286	403508075254501	Orendach, Robert	--	1910	W	U
1287	403525075420101	Ryder Truck, Inc.	--	--	W	H
1289	403442075373501	Lehigh County Authority	William Stothoff Co.	1970	W	P
1290	403356075365901	Lehigh County Authority	William Stothoff Co.	1970	W	P
1291	403449075384701	Lehigh County Authority	Harrisburg's Kohl Bros.	1971	W	P
1292	403524075362401	Lehigh County Authority	Harrisburg's Kohl Bros.	1972	W	P
1293	403230075321201	Lehigh County Authority	C.S. Garber & Sons, Inc.	1974	W	P
1294	403143075331202	Lehigh County Authority	Harrisburg's Kohl Bros.	1973	W	P
1295	403149075354101	Lehigh County Authority	C.S. Garber & Sons, Inc.	1971	W	P
1297	403504075371901	G.R. Insurance Co.	--	1900	U	U
1298	403404075330601	Pearl, Don	--	1975	W	H
1299	403317075311301	Rodale, Robert	C.S. Garber & Sons, Inc.	1964	W	H
1300	403143075352901	Lehigh County Authority	C.S. Garber & Sons, Inc.	1972	W	P
1305	403902075301502	Whitehall Twp. Authority	Terry M. Mayer	1984	W	P
1306	403818075304101	Whitehall Twp. Authority	Terry M. Mayer	1984	U	U
1307	403759075291301	Whitehall Twp. Authority	Terry M. Mayer	1984	Z	U
1308	403742075291201	Whitehall Twp. Authority	Terry M. Mayer	1984	U	U
1309	403819075302001	Whitehall Twp. Authority	Terry M. Mayer	1984	Z	U
1312	403742075343701	S. Whitehall Twp. Authority	--	1966	W	P
1313	403531075333801	S. Whitehall Twp. Authority	R.H. Odenheiner Co.	1970	W	P
1314	403533075334201	S. Whitehall Twp. Authority	R.H. Odenheiner Co.	1982	W	P
1315	403457075315401	S. Whitehall Twp. Authority	R.H. Odenheiner Co.	1985	W	P
1318	403224075304701	Emmaus Borough	Layne-New York Co., Inc.	1973	W	P
1319	403403075375501	Lehigh County Authority	Eichelberger Well Drlg., Inc.	1985	W	P
1320	403453075322301	Hunsicker, Horace	Kermit S. Snyder	1963	W	Z
1321	403134075335001	Lehigh County Authority	C.S. Garber & Sons, Inc.	1976	W	P
1322	403545075311901	Lehigh County Authority	--	1969	W	P
1323	403357075312101	Lehigh County Authority	--	1976	W	P
1326	403406075331501	Wescosville Professional Park	--	1986	W	H
1327	403342075341001	Duford, Rolland	--	1986	W	H
1331	403725075271901	AT&T Technologies	Terry M. Mayer	1979	W	N
1332	403057075342501	Mack Trucks, Inc.	William Stothoff Co.	1974	W	N
1335	403818075300302	Whitehall Twp. Authority	--	1975	W	P
1336	403710075342101	Alpo Pet Foods, Inc.	Moody Drilling Co.	1970	W	N
1337	403700075341201	Alpo Pet Foods, Inc.	Moody Drilling Co.	1972	W	N
1338	403708075341901	Alpo Pet Foods, Inc.	Eichelberger Well Drlg., Inc.	1983	W	N
1339	403818075300303	Whitehall Twp. Authority	--	1985	W	P
1340	403856075311001	Whitehall Twp. Authority	--	1986	W	P
1341	403024075353401	Alburtis Water Authority	Joseph M. Mayer	1977	W	P
1342	403839075280301	Tarketts, Inc.	R.H. Odenheiner Co.	1971	W	N
1343	403229075394701	Shellhamer, Daniel	R.H. Odenheiner Co.	1959	W	P
1344	403226075395302	Shellhamer, Daniel	R.H. Odenheiner Co.	1963	W	P
1345	403230075393801	Shellhamer, Durell	Terry M. Mayer	1970	W	C
1346	403647075325001	Country Club Gardens Water Co.	R.H. Odenheiner Co.	1974	W	P
1347	403647075325002	Country Club Gardens Water Co.	R.H. Odenheiner Co.	1971	W	P
1348	403648075331101	Country Club Gardens Water Co.	Joseph M. Mayer	1974	W	P
1349	403432075324401	Cedarbrook	Larry D. Welshhans	1977	W	T
1351	403401075375001	Muth	--	--	W	H
1353	403400075385501	Unknown	--	--	W	H
1354	403423075385501	Lehigh County Authority	--	1985	O	U
1355	403422075374201	Stroh Brewery Co.	Pennsylvania Drilling Co.	1985	W	N
1356	403432075375401	Stroh Brewery Co.	Pennsylvania Drilling Co.	1985	O	U
1357	403418075370201	Stroh Brewery Co.	Pennsylvania Drilling Co.	1985	O	U
1358	403428075370201	Torola	--	--	W	C
1359	403648075331102	Country Club Gardens Water Co.	R.H. Odenheiner Co.	1972	W	P
1369	403757075321901	IMC Pitman-Moore, Inc.	--	--	W	N
LE-Sp-14	403543075285301	City of Allentown (Crystal Spring)	--	--	W	P
Sp-15	403447075331801	City of Allentown (Schantz Spring)	--	--	W	P

Table 18.--Records of selected wells and springs--Continued

Aquifer code	Depth of well (feet)	Depth cased (feet)	Casing diameter (inches)	Elevation of land surface (feet)	Water level (feet)	Date water level measured	Reported yield (gallons per minute)	Reported specific capacity (gal/min)/ft	Local number
				LEHIGH COUNTY--Continued					
367EPLR	170	122	12	315	--	--	--	--	LE-1107
367EPLR	164	126	12	320	--	--	--	--	1108
367EPLR	168	140	12	310	--	--	--	--	1109
371ALNN	100	--	6	250	--	--	40	--	1274
371ALNN	100	--	8	320	--	--	100	--	1275
364JKBGR	130	--	--	50	18.8 R	06-26-1984	--	--	1284
371ALNN	240	107	8	410	25.8 R	07-03-1984	325	4.6	1285
374LSVL	--	--	--	520	6.05 M	07-16-1984	--	--	1286
364BKMN	--	--	--	460	--	07-26-1984	--	--	1287
364JKBGC	400	52	12	450	79.0 R	05-01-1984	1,010	33.6	1289
364BKMN	350	184	10	430	56 R	05-01-1984	1,000	200	1290
364BKMN	400	37	24	470	75 R	1984	695	23	1291
364JKBGC	400	37	24	465	61.0 R	05-01-1984	850	23	1292
371ALNN	295	152	8	410	115	05-01-1984	367	52	1293
371ALNN	130	40	6	400	64.0 R	05-01-1984	200	29	1294
371ALNN	184	71	8	400	55.0 R	05-01-1984	500	125	1295
364JKBGR	20	--	--	475	11.1 M	08-09-1984	--	--	1297
371ALNN	--	--	6	400	--	08-09-1984	--	--	1298
371ALNN	--	--	6	375	63.5 R	08-09-1984	--	--	1299
371ALNN	360	135	8	430	67 R	05-01-1984	200	1.1	1300
367EPLR	150	60	8	365	88.9 R	09-10-1984	300	17	1305
371ALNN	280	90	10	395	--	--	20	--	1306
371ALNN	400	23	6	400	--	--	10	.12	1307
367EPLR	400	43	6	320	32 R	07- -1984	39	.13	1308
371ALNN	300	80	6	385	150 R	09- -1984	3	.02	1309
367EPLR	--	--	--	370	62	07-28-1982	65	65	1312
364BKMN	144	--	--	430	47 R	05-01-1984	80	11	1313
364BKMN	300	60	8	430	63 R	05-02-1984	475	26.4	1314
371ALNN	262	125	8	315	27.2	03-11-1985	481	10	1315
371ALNN	400	150	10	370	45 R	09-19-1973	546	26	1318
364BKMN	200	119	12	450	55.9 M	06-27-1985	2,000	330	1319
371ALNN	355	69	8	390	60 R	12-19-1963	--	--	1320
371ALNN	272	215	8	435	92 R	01-12-1976	298	7.6	1321
371ALNN	400	68	8	470	155	01-23-1969	90	3	1322
371ALNN	425	83	8	440	123 R	07-27-1976	90	.71	1323
371ALNN	85	--	6	390	59.8 R	01-09-1986	--	--	1326
371ALNN	145	--	6	460	116 R	01-09-1986	--	--	1327
371ALNN	170	91	8	295	40 R	05-07-1986	475	4.8	1331
371ALNN	355	185	8	410	43 R	12-10-1974	200	2.4	1332
371ALNN	270	59	6	415	142 R	1985	50	8.3	1335
364BKMN	522	170	8	1,420	96 R	04-22-1970	500	125	1336
361MRBG	410	87	8	460	121 R	02-29-1972	120	120	1337
364BKMN	700	252	12	440	125 R	11-08-1983	600	150	1338
371ALNN	400	--	--	415	--	--	--	--	1339
371ALNN	350	--	--	370	--	--	548	180	1340
374LSVL	216	114	8	425	39 R	03-10-1977	125	2.8	1341
364BKMN	430	36	15	275	30 R	01-15-1971	1,080	22	1342
361BSKL	207	--	6	500	--	--	--	--	1343
361BSKL	293	--	6	460	--	--	--	--	1344
361BSKL	97	--	6	450	--	--	--	--	1345
364BKMN	227	65	6	470	73 R	10-20-1987	72	72	1346
364BKMN	350	95	6	470	70 R	01-07-1971	60	120	1347
364BKMN	401	87	6	510	80 R	09-10-1974	55	.32	1348
371ALNN	300	64	8	370	45 R	08-24-1977	360	--	1349
364BKMN	140	--	6	450	--	--	--	--	1351
364BKMN	55	--	--	465	--	--	--	--	1353
364BKMN	45	6	4	460	--	--	--	--	1354
364BKMN	250	--	--	430	--	--	--	--	1355
364BKMN	228	85	6	440	--	--	--	--	1356
364BKMN	230	58	6	435	--	--	--	--	1357
364BKMN	80	--	--	440	--	--	--	--	1358
364BKMN	350	93	6	510	126 R	03-17-1972	65	2.7	1359
367EPLR	160	110	12	310	--	--	--	--	1369
371ALNN	--	--	--	265	--	--	2,800	--	LE-Sp-14
364BKMN	--	--	--	340	--	--	8,500	--	Sp-15

*U.S. GOVERNMENT PRINTING OFFICE:1991-612-567